ALLOYS OF IRON RESEARCH, MONOGRAPH SERIES

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THE ALLOYS OF IRON AND CHROMIUM

Vol. II—HIGH-CHROMIUM ALLOYS

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THE ALLOYS OF IRON AND CHROMIUM

VOL. II—HIGH-CHROMIUM ALLOYS

BY

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AND

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ALLOYS OF IRON RESEARCH

MONOGRAPH SERIES

These monographs are a concise but comprehensive critical summary of research on iron and its alloys as reported in the technical literature of the world. They contain a discussion of all available data on binary and higher ferrous alloy systems, and on the effect of the alloying elements on carbon steel and on simple and complex alloy steels and special alloy cast irons They provide a reliable foundation for further research and supply to the practical metallurgist, steel worker, foundryman, and engineer the essential information now scattered through more than two thousand journals and textbooks in many languages.

The authors are responsible for selection and evaluation of the data, for arrangement of subject matter, and for style of presentation. Each book, however, has been reviewed in manuscript by men especially qualified to criticize all statements. Indebtedness for this cooperation is recognized in the Acknowledgments. Finally, each manuscript has been reviewed and approved for publication by the Iron Alloys Committee

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PREFACE

This volume, the eleventh in order of publication and the tenth of the regular monograph series, is the second and final part of a review and summary of important published information and available unpublished data on the alloys of iron and chromium. It deals with alloys containing more than 10 per cent chromium and includes data on those materials commonly known as "stainless" and "heat-resisting" steels. Many of the alloys discussed in this volume contain relatively large amounts of alloying elements in addition to chromium. Data embodying the results of research on such complex alloys—of which the 18 per cent chromium, 8 per cent nickel material is most important—are summarized in this volume, with the exception, however, of those containing more nickel than chromium, which are covered in "The Alloys of Iron and Nickel, Volume I, Special-purpose Alloys."

Of approximately nine thousand articles dealing with chromium as an alloying element which were assembled in the preliminary search of the literature, 528 dealing with high-chromium materials were considered of sufficient importance to be discussed in this volume and are appended to the text as a chronological bibliography. The bibliographies of this volume and of Volume I of this monograph comprise slightly more than one thousand references. Unpublished data—of which there is a considerable amount in this volume—which are not credited were obtained at Union Carbide and Carbon Research Laboratories, Inc.; the source of all other unpublished data is acknowledged in the text.

Although this volume is, so far as possible, complete in itself, it was necessary to refer briefly to some of the material discussed in detail in Volume I. This is particularly true of the iron-chromium and iron-chromium-carbon equilibrium diagrams and matter pertaining to general rates of reaction. Attention is called to Chapter V in Volume I which covers the whole field of iron-chromium alloys broadly; although this is not specifically a report of research, it is essential for comprehensive understanding to those not wholly familiar with the field.

Preparation of this volume differs from others in this series in several major respects. The field covered is one of relatively recent metallurgical interest. Many of the phenomena involved are still to be explained satisfactorily, and many of the hypotheses advanced, while commonly accepted, still require rigid proof. The entire art and science of these steels is rapidly changing; in probably no other branch of ferrous metallurgy do we find so many changes, not only in fundamental concepts concerning the nature of these steels, but also in their actual composition. In view of this, it is not infrequent that developments are described in the patent literature and not in the technical literature. While no attempt has been made to search the patent literature and cover it in detail, it has been necessary frequently to refer to published patents to cover specific developments. Nomenclature is not well established. This is particularly true of the so-called austenitic steels where, for example, "annealing" means "heating and quenching"; this has been avoided in this volume. The use of the word "stainless" is common to designate most of the steels discussed in this volume. Each of them may be stainless in a given environment but may stain and even corrode badly in other environments. Further, there is commonly no clear distinction between irons and steels in this group. The low-carbon ferritic alloys are generally referred to as irons and the higher carbon ferritic, pearlitic, and martensitic alloys which undergo a phase change at some elevated temperature are known as steels. Again, the low-carbon austenitic alloys are known as steels. The lines of demarcation are not sharp and, except where behavior of the material is highly characteristic, the authors have attempted to avoid the use of either term. Furthermore, the whole subject of corrosion resistance is one that does not lend itself to scientific measurement, and one is forced to such vagueness as "almost not attacked" or "practically corrosion-resistant" in dealing with this subject.

There is another difficulty in terminology which should be mentioned. The chemical element of atomic number 41 is variously called "columbium" and "niobium"; the latter is commonly used in England and other European countries. Unfortunately there is no international agreement among chemists regarding the use of either name; thus, in the list of atomic weights prepared by the Committee on Atomic Weights of the International Union of Chemistry the element is called "columbium" in the American edition and "niobium (columbium)" in the British edition. The authors of this book would have liked to share the impartiality of the International Committee and use both terms, but as this was impracticable, the word "columbium" as given in the official American list of atomic weights has been used. This conforms also with the advice of Mellor, the British authority, who states in his "Comprehensive Treatise on Inorganic and Theoretical Chemistry":

> Since niobium discovered by H. Rose in 1844 is the same element as columbium discovered by C. Hatchett over 40 years earlier, it was pointed out by J. L. Smith, and P. Nicolardot, very properly, that it is more fitting to retain the term columbium for the element, and abandon niobium.

Most of the alloys discussed in this volume come under the broad classification of "stainless steels"; this subject, as a whole, has been treated at length in recent books by Monypenny and Thum. These should be considered as major references, and a student interested in any particular phase of the subject covered in this monograph should refer to them. It will be noted at once that the organization of this volume and the general approach to the subject matter differ radically from those of Monypenny and of Thum, but this in no way signifies any lack of appreciation on the part of the authors for either of these works, each of which has been invaluable in the preparation of the subject matter.

A. B. Kinzel,
Russell Franks.

New York,
December, 1939.

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The preparation of the first, as well as of the second, volume of this monograph was undertaken with the knowledge that the staff of Union Carbide and Carbon Research Laboratories, Inc., would cooperate to the fullest extent. It is a pleasure to acknowledge this assistance, which has been invaluable. Dr. F. M. Becket, widely known authority on alloys of iron and chromium, has given frequently of his counsel, as has J. H. Critchett, Vice President of the Union Carbide and Carbon Research Laboratories, Inc., and of the Electro Metallurgical Company. Various members of the staff assisted in reviewing the literature and assembled much of the data. The authors are especially indebted to C. O. Burgess for preparation of the chapter on high-chromium cast irons, to C. O. Burgess and W. D. Forgeng for their assistance in the preparation of the iron-chromium-manganese diagram, and to W. D. Forgeng for assistance in preparation of the iron-chromium-nickel diagram. They also wish to thank S. M Norwood, of the Electro Metallurgical Company, for his advice on many specific points. Special acknowledgment is due the editorial staff of Alloys of Iron Research who have given much more than their usual cooperation and assistance.

All the members of the Iron Alloys Committee have read the manuscript of this volume, and various drafts of each chapter have been read and criticized by metallurgists expert in their respective fields. All criticisms have been given due weight, and many revisions have resulted therefrom. Special acknowledgment of both oral and written discussion is made to E. E. Thum, W. H. Hatfield, and J. H. G. Monypenny. The final manuscript has resulted from the assistance of these collaborators and of those named below. However, this cooperation does not necessarily indicate their complete approval of any specific portion of the manuscript.

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CONTENTS

PAGE

PREFACE vii

ACKNOWLEDGMENTS xi

CHAPTER I

INTRODUCTION 1

The Phase Relations—General Effects of Chromium in Iron and Steel—Metallurgical Fundamentals of Stainless Steels.

CHAPTER II

MELTING HIGH-CHROMIUM STEELS 15

Manufacture of High-chromium Steels with Ferrochromium—Manufacture of Low-carbon Grades with Chromium Ore—Remelting High-chromium Steel Scrap—Pouring Practice—Authors' Summary.

CHAPTER III

FABRICATION OF 12 TO 30 PER CENT CHROMIUM STEELS . . . 41

Effect of Composition on Hot Working the Ingots—Manufacture of Bars, Rods, and Tubes—Manufacture of Wire and Other Cold-worked Products—Manufacture of Plate, Sheet, and Strip—Authors' Summary.

CHAPTER IV

LOW-CARBON STEELS CONTAINING 10 TO 18 PER CENT CHROMIUM. . 57

Mechanical Properties—Mechanical Properties of Modified Iron-chromium Alloys—Physical Constants—Corrosion—Castings—Welding—Authors' Summary.

CHAPTER V

MEDIUM-CARBON STEELS CONTAINING 10 TO 18 PER CENT CHROMIUM. 116

Structure and Transformations of Medium-carbon 10 to 18 Per Cent Chromium Steels—Effect of Heat Treatment on Properties—Corrosion Resistance—Mechanical Properties at Elevated Temperatures—Modified 10 to 18 Per Cent Chromium Steels—Authors' Summary.

CHAPTER VI

HIGH-CARBON STEELS CONTAINING 10 TO 18 PER CENT CHROMIUM 155

Die Steels—Valve Steels—Authors' Summary.

PAGE

CHAPTER VII

PLAIN AND MODIFIED CHROMIUM STEELS CONTAINING 20 TO 35 PER CENT CHROMIUM 173

Manufacture and Fabrication—Physical Constants—Mechanical Properties—Corrosion and Oxidation Resistance—Modified 20 to 30 Per Cent Chromium Steels—Authors' Summary.

CHAPTER VIII

CHROMIUM CAST IRON CONTAINING 12 TO 35 PER CENT CHROMIUM 228

General Characteristics of High-chromium Cast Irons—Effect of Heat Treatment—Special Properties—Composition and Application—Authors' Summary.

CHAPTER IX

CONSTITUTION OF COMPLEX IRON-CHROMIUM ALLOYS 261

The Iron-chromium-nickel System—Other Systems—Authors' Summary

CHAPTER X

MANUFACTURE AND FABRICATION OF AUSTENITIC CHROMIUM-NICKEL STEELS 283

Melting and Working—Miscellaneous Fabricating Operations—Welding—Authors' Summary.

CHAPTER XI

PROPERTIES OF AUSTENITIC CHROMIUM-NICKEL STEELS 302

Static Properties at Normal Temperatures—Dynamic Properties at Normal Temperatures—Cast and Welded Austenitic Nickel-chromium Steels—Miscellaneous Physical Properties—Effect of Temperature—Authors' Summary

CHAPTER XII

THE RESISTANCE OF THE AUSTENITIC CHROMIUM-NICKEL STEELS TO OXIDATION AND CORROSION 361

Oxidation of Chromium-nickel Steels—Corrosion of Chromium-nickel Steels in Various Media—Pitting and Intergranular Corrosion — Corrosion in Internal-combustion Engines — Authors' Summary

CHAPTER XIII

MODIFIED AUSTENITIC CHROMIUM-NICKEL STEELS. 403

Chromium-nickel-silicon Steels—Chromium-nickel-tungsten Steels—Chromium-nickel-molybdenum Steels—Effect of Titanium on Austenitic Chromium-nickel Steels—Effect of Columbium on Austenitic Chromium-nickel Steels—Miscellaneous Modified Chromium-nickel Steels—Authors' Summary.

PAGE

CHAPTER XIV

CHROMIUM-MANGANESE STEELS 438

General Survey of High Chromium-manganese Steels—Manufacture and Properties of Steels Containing 16 to 20 Per Cent Chromium and 8 to 10 Per Cent Manganese—Effect of Other Elements—Intergranular Corrosion—Authors' Summary.

CHAPTER XV

IRON-CHROMIUM-ALUMINUM ALLOYS 472

Manufacture and Mechanical Properties—Electric Resistance and Other Properties—Authors' Summary.

APPENDIX 487

BIBLIOGRAPHY 489

NAME INDEX 523

SUBJECT INDEX 533

THE ALLOYS OF IRON AND CHROMIUM

VOLUME II

HIGH-CHROMIUM ALLOYS

CHAPTER I

INTRODUCTION

The Phase Relations—General Effects of Chromium in Iron and Steel —Metallurgical Fundamentals of Stainless Steels

Chromium, it was stated in the first volume of this monograph, is one of the most important alloying elements in modern ferrous metallurgy. This becomes especially apparent in a study of the irons and steels containing more than 10 per cent chromium. Industrial applications of such materials, which include the important corrosion- and heat-resisting alloys, are increasing; from the original few pounds of cutlery steel made in a crucible by Brearley, production has increased so that it is now measured in terms of thousands of tons, valued by the steel industry at millions of dollars. The economic value to other industries and the benefits to humanity are of a still greater order of magnitude. Industries have been built on apparatus and processes made economically possible by these steels. The benefits to mankind resulting from a series of steels not subject to progressive corrosion and oxidation have been stressed so often and are so obvious that it is unnecessary to dwell on them further, except to recall that man is only too ready to accept the obvious without realizing its significance.

It is the purpose of this volume to summarize the facts concerning steels containing more than 10 per cent chromium, with or without additional elements, with special reference to physical and chemical effects. It is further the intention that this volume be essentially complete in itself, although some special matter pertinent to high-chromium steels is discussed at length in the first volume of this monograph and, indeed, the first five chapters of that volume are as necessary to an understanding of the high- as of the low-chromium steels.

As pointed out in Volume I, the high-chromium steels date back to the work of Brearley, Haynes, Strauss, Maurer, Becket, and Hatfield, and it is still true that no element other than chromium has been found that imparts the desired corrosion and oxidation resistance to wrought iron-base alloys. The basic features of the iron-chromium system, discussed in detail in Volume I, are reviewed here for ready reference.

A. THE PHASE RELATIONS

Proper comprehension of phase relations is essential to an understanding of the various phenomena characteristic of high-chromium steels, and indeed most of these phenomena have been directly related to phase changes. The phase relations apply essentially to the end points of various reactions but do not take into consideration the rates of such reactions. This part of the story is told in detail in later chapters as the specific phenomena are discussed. It has often been said that, other than iron, carbon is the most important element in any steel; this certainly applies to the higher chromium steels. Without an understanding of the phase diagrams the entire science and art of high-chromium steels would be in a state of great confusion, and much of the rapid industrial advance must be attributed to the fundamental work that accompanied the industrialization of the materials.

1. The Iron-chromium System.—The iron-chromium diagram consists of one liquid and three solid phases (Fig. 1). The boundaries of the liquid-phase region coincide at 22 per cent chromium and 1505°C. (2740°F.). Of the solid phases, alpha phase (ferrite) is the most common. In carbon-free alloys, the gamma phase (austenite) occurs only in those having less than about 11.5 per cent chromium, and within this region it does not exist above 1400°C. (2550°F.) or below 855°C. (1570°F.). The third solid phase, designated "sigma," originates in the probable formation of the compound FeCr. This phase does not exist above 850°C. (1560°F.) or outside the range 30 to 65 per cent chromium. Work completed since the publication of Volume I and reported by Becket(488) has resulted in a diagram showing the range of existence of sigma phase in industrial alloys; this is given in Fig. 2. It will be seen that in such alloys the concentration limits at low temperatures are roughly 30 and 55 per cent chromium. Quantitative changes in these diagrams are to be expected as laboratory investigations progress, but it is improbable that the qualitative details will be altered.

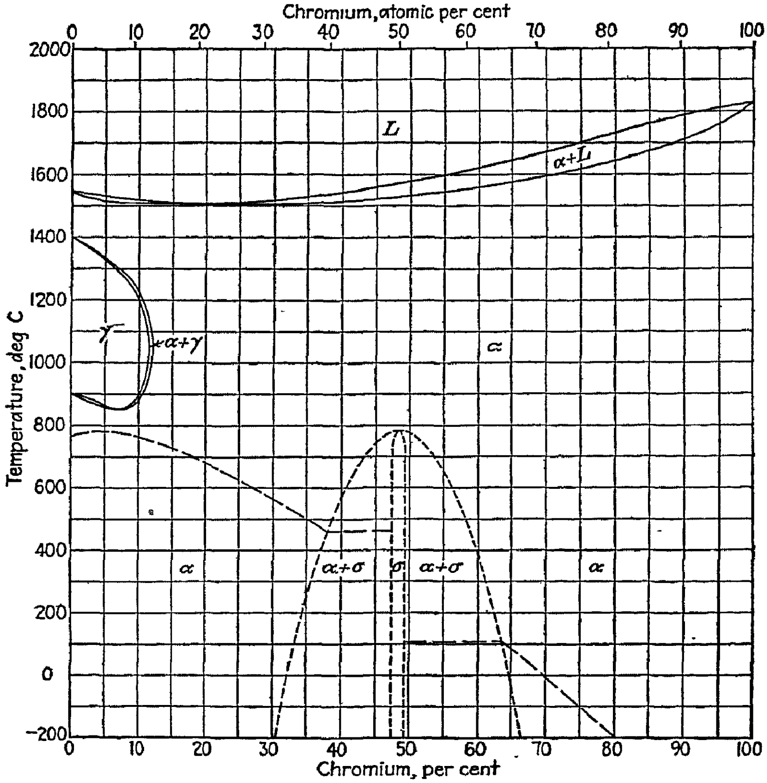

FIG. 1.—The proposed iron-chromium equilibrium diagram. (*Kinzel and Crafts.*(460))

2. The Iron-chromium-carbon System.—The iron-chromium-carbon system is based upon the iron-carbon, the iron-chromium, and the chromium-carbon systems. The chromium-carbon system is complex; it leads to a highly involved ternary diagram, in which the carbides Cr_4C, Cr_7C_3, and Cr_3C_2 participate. Perhaps the most simple approach to the diagram is by way of constant-carbon sections parallel to the iron-chromium plane.

A series of such sections is given in the first volume (Fig. 37, page 65). With carbon at approximately zero, the gamma phase disappears at about 11.5 per cent chromium; the alpha-plus-gamma region is narrow. As the carbon increases to approximately 0.1 per cent, the chromium limit of the gamma-phase region is extended to approximately 13 per cent, but the limit of its existence (in two-phase alloys) is extended to about 18 per cent chromium. At 0.4 per cent carbon, the limits are respectively about 18 per cent and some higher chromium content.

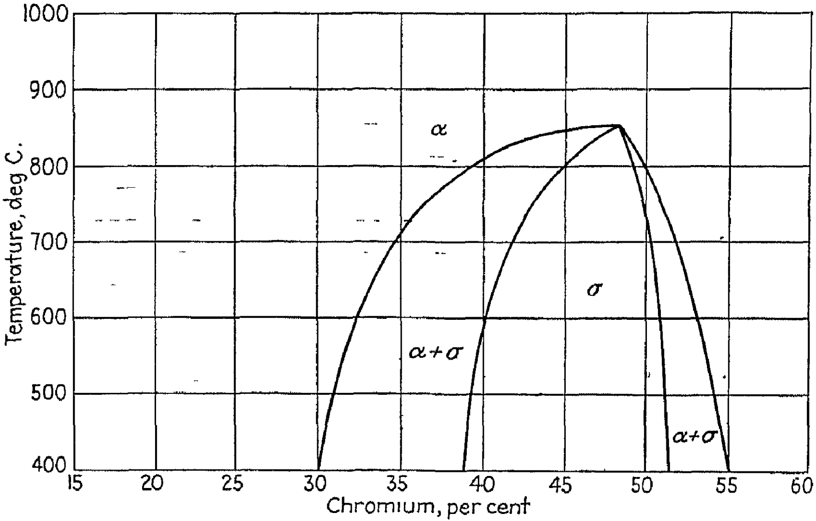

FIG. 2.—The sigma-phase region of the iron-chromium diagram. (*Becket* (488))

3. Transformations in Chromium Steels.—Small amounts of chromium increase the temperature of the A_1 transformation (gamma phase $\rightleftharpoons$ alpha phase + carbide), but this behavior disappears in alloys of the chromium contents discussed in this volume. In many of the steels under consideration, the alpha-gamma transformation is non-existent, and in many others it occurs only in localized areas. The fact that chromium increases the sluggishness of transformation on cooling is especially noticeable in the higher chromium steels, and this sluggishness results in phenomena frequently undesirable, but of major industrial importance. This may be seen readily from the right-hand portion of the structural diagram (Volume I, Fig. 55), for alloys cooled from 950°C. (1740°F.). In the high-chromium steels, particularly those that are not modified by appreciable amounts of other elements, there is a strong tendency for most of the carbon to segregate in the small amount of austenite that may be formed. This is directly allied to the greater solubility of carbon in this phase. Accordingly, at the rolling temperature of plain chromium steels containing from 12 to 18 per cent chromium, there may be streaks of austenite that contain the greater portion of the carbon in the steel. This is important because the major portion of the steel, being ferritic, undergoes no transformation, whereas the smaller portion, which is austenitic at elevated temperatures, changes to martensite or pearlite on cooling. Thus it is necessary to consider transformations in local areas when dealing with the high-chromium steels.

B. GENERAL EFFECTS OF CHROMIUM IN IRON AND STEEL

The general effects of chromium in iron and steel of both high and low chromium content are discussed in Chapter V of the first volume, and the reader who is not thoroughly versed in this field is urged to study that chapter. In the high- as well as in the low-chromium steels the relationship of chromium and carbon is all-important, and this is true not only of transformations but also of chemical properties.

For the purpose of presentation, the corrosion- and oxidation-resistant irons and steels have been divided into various groups, based on chromium content, structural constitution, and sometimes properties. The first group comprises irons and steels with 10 to 16 or 18 per cent chromium; the next includes those with 16 or 18 to 22 per cent chromium; and the last, those with more than 22 per cent chromium. The austenitic steels have been grouped separately for obvious reasons. There is some question about these lines of demarcation, but the scheme is workable and useful.

4. General Effects of Chromium on Manufacture and Heat Treatment.—In the melting of high-chromium steels the governing factor is that chromium combines with carbon and with oxygen more readily than does iron. To produce low-carbon steels of high quality economically the general procedure is to add chromium (as ferrochromium containing some carbon) to a steel bath containing less than the required final carbon percentage and having a low oxygen content. The carbon content of the bath can be lowered after chromium has been added, but this results in simultaneous oxidation of chromium. Recovery of the lost chromium necessitates reduction from the slag. Similarly, chromium oxides are formed if the oxygen content of the bath is too high at the time of chromium addition; part of these pass into the slag—where they can be reduced by silicon or other suitable agents—and others remain in the steel. Unless very special practice is followed, the residual oxides are likely to appear in the final product as inclusions to an undesirable degree.

The use of especially low carbon ferrochromium is desirable—if not essential—if a low-carbon chromium steel is to be produced. (The so-called "direct process," making use of chrome ore, and the process making use of high-carbon ferrochromium are based on the aforementioned reduction-by-silicon step.) Various grades of ferrochromium containing as little as 0.06 per cent carbon are commonly used, and special grades containing as little as 0.03 per cent carbon are available industrially. High-chromium steel scrap of the proper analysis is also used extensively together with the various grades of ferrochromium.

The forging and working of high-chromium steels require special care, particularly with respect to temperature. Suitable initial hot-working temperatures are about 1100°C. (2010°F.) for the plain chromium steels and 1150°C. (2100°F.) for the austenitic chromium-nickel steels. The upper limit varies with the steel, but about 1200°C. (2190°F.) is more or less generally applicable as the maximum initial hot-working temperature. (Ranges for specific compositions are given in the appropriate chapters.) The steels may be cold worked, but again special care and frequent softening treatments are necessary. They may be cut with the oxyacetylene torch by using special techniques such as the zigzag procedure or the iron oxide fluxing system.

In general—with the exception of the delta-gamma transformation(191)—the transformation rates of high-chromium steels are relatively low. (In some instances, there are no solid-state transformations, or they occur only in localized areas.) For example, a cutlery steel containing about 0.3 per cent carbon and 13 per cent chromium—which is roughly the "eutectoid" composition*—may be cooled at a much lower rate than a eutectoid carbon steel to obtain an equivalent structural composition. Unfortunately, the Bain *S* curve for this system is not yet available so that a complete quantitative picture is lacking. Rates of transformation are changed still further by the addition of nickel as well as chromium.

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* Strictly speaking, it is improper to use this term in connection with such alloys.

5. General Effects of Chromium on Physical and Chemical Properties.—Carbon has a greater effect on the physical properties of high-chromium steels than on those of plain carbon and low-chromium steels so that it is possible, by varying chromium and carbon contents, to obtain an even wider variety of materials, ranging from low-strength high-ductility irons and steels to those that are hard and brittle. Chemical properties are also greatly affected by carbon. In general, the higher the chromium and the lower the carbon, the more resistant is the alloy to certain types of corrosion. By changing this chromium-carbon relationship the corrosion resistance may be lowered considerably. Further modification of physical and chemical properties may be obtained by adding nickel. This leads to a whole new category of alloys, the austenitic stainless steels, in which three variables—carbon, chromium, and nickel—must be controlled.

In the annealed condition, there is little change in strength of low-carbon chromium steels in the 12 to 22 per cent chromium range. In the quenched and tempered condition, however, there is definite reduction of hardness and strength as the chromium content is increased from 12 per cent. If, however, an austenite-forming element is added to these soft low-carbon iron-chromium alloys, hardness and strength increase until the composition is such that austenite becomes the stable phase at room temperature. The austenitic structure is accompanied by a change in properties to slightly higher strength, lower yield ratio, and higher ductility, as compared with the annealed ferritic steels.

Such steels derive their important characteristics from the fact that modifying additions, such as nickel, shift the position of the gamma field so that even the low-carbon high-chromium steels are austenitic at elevated temperatures. Sluggish transformation causes persistence of the austenite at room temperature upon rapid cooling from a suitable elevated temperature. Steels containing 18 per cent chromium, 8 per cent nickel, and less than 0.10 per cent carbon are typical of the industrial austenitic stainless steels. A complete discussion of the phase relationships in the iron-chromium-nickel system as well as some discussion bath can be lowered after chromium has been added, but this results in simultaneous oxidation of chromium. Recovery of the lost chromium necessitates reduction from the slag. Similarly, chromium oxides are formed if the oxygen content of the bath is too high at the time of chromium addition; part of these pass into the slag—where they can be reduced by silicon or other suitable agents—and others remain in the steel. Unless very special practice is followed, the residual oxides are likely to appear in the final product as inclusions to an undesirable degree.

The use of especially low carbon ferrochromium is desirable—if not essential—if a low-carbon chromium steel is to be produced. (The so-called "direct process," making use of chrome ore, and the process making use of high-carbon ferrochromium are based on the aforementioned reduction-by-silicon step.) Various grades of ferrochromium containing as little as 0.06 per cent carbon are commonly used, and special grades containing as little as 0.03 per cent carbon are available industrially. High-chromium steel scrap of the proper analysis is also used extensively together with the various grades of ferrochromium.

The forging and working of high-chromium steels require special care, particularly with respect to temperature. Suitable initial hot-working temperatures are about 1100°C. (2010°F.) for the plain chromium steels and 1150°C. (2100°F.) for the austenitic chromium-nickel steels. The upper limit varies with the steel, but about 1200°C. (2190°F.) is more or less generally applicable as the maximum initial hot-working temperature. (Ranges for specific compositions are given in the appropriate chapters.) The steels may be cold worked, but again special care and frequent softening treatments are necessary. They may be cut with the oxyacetylene torch by using special techniques such as the zigzag procedure or the iron oxide fluxing system.

In general—with the exception of the delta-gamma transformation(191)—the transformation rates of high-chromium steels are relatively low. (In some instances, there are no solid-state transformations, or they occur only in localized areas.) For example, a cutlery steel containing about 0.3 per cent carbon and 13 per cent chromium—which is roughly the "eutectoid" composition*—may be cooled at a much lower rate than a eutectoid carbon steel to obtain an equivalent structural composition. Unfortunately, the Bain *S* curve for this system is not yet available so that a complete quantitative picture is lacking. Rates of transformation are changed still further by the addition of nickel as well as chromium.

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* Strictly speaking, it is improper to use this term in connection with such alloys.

5. General Effects of Chromium on Physical and Chemical Properties.—Carbon has a greater effect on the physical properties of high-chromium steels than on those of plain carbon and low-chromium steels so that it is possible, by varying chromium and carbon contents, to obtain an even wider variety of materials, ranging from low-strength high-ductility irons and steels to those that are hard and brittle. Chemical properties are also greatly affected by carbon. In general, the higher the chromium and the lower the carbon, the more resistant is the alloy to certain types of corrosion. By changing this chromium-carbon relationship the corrosion resistance may be lowered considerably. Further modification of physical and chemical properties may be obtained by adding nickel. This leads to a whole new category of alloys, the austenitic stainless steels, in which three variables—carbon, chromium, and nickel—must be controlled.

In the annealed condition, there is little change in strength of low-carbon chromium steels in the 12 to 22 per cent chromium range. In the quenched and tempered condition, however, there is definite reduction of hardness and strength as the chromium content is increased from 12 per cent. If, however, an austenite-forming element is added to these soft low-carbon iron-chromium alloys, hardness and strength increase until the composition is such that austenite becomes the stable phase at room temperature. The austenitic structure is accompanied by a change in properties to slightly higher strength, lower yield ratio, and higher ductility, as compared with the annealed ferritic steels.

Such steels derive their important characteristics from the fact that modifying additions, such as nickel, shift the position of the gamma field so that even the low-carbon high-chromium steels are austenitic at elevated temperatures. Sluggish transformation causes persistence of the austenite at room temperature upon rapid cooling from a suitable elevated temperature. Steels containing 18 per cent chromium, 8 per cent nickel, and less than 0.10 per cent carbon are typical of the industrial austenitic stainless steels. A complete discussion of the phase relationships in the iron-chromium-nickel system as well as some discussion of the rôle of carbon in this system will be found in Chapter IX. The essential fact, however, is that austenite is thermodynamically unstable in these steels at ordinary temperature; partial transformation to ferrite, or ferrite and carbide, may occur under certain conditions. Conditions conducive to transformation include heating to the medium-temperature range and mechanical stress. The effects of partial transformation are discussed in detail in subsequent chapters. In addition, the austenite is frequently supersaturated with carbon at temperatures which, given sufficient time, permit carbide precipitation which produces effects frequently undesirable.

Another series of alloys, only partly austenitic at elevated temperatures, is possible. The low-carbon 18 per cent chromium, 8 per cent manganese steels are typical of such alloys; these too are discussed in detail in the proper place. In these materials, the structure may be half austenitic and half ferritic at some elevated temperature. Again, largely owing to the sluggishness imparted by chromium, the austenitic phase may be retained as such on rapid cooling, thus yielding a metal that is half ferritic and half austenitic at room temperature. This austenite also partially changes to ferrite under suitable temperature-stress conditions. Such steels have properties peculiar to themselves and are indeed a separate chapter in the field of stainless steels. They are especially interesting because of the possibility of observing the effects of the larger proportions of ferrite in comparison with those of the smaller proportions of ferrite in iron-chromium-nickel alloys; this was discussed in some detail by Becket.(488)

As the chromium content of low-carbon steels is increased beyond about 10 per cent, the resistance to chemical attack by specific media increases markedly; this is especially true of resistance to oxidation. The resistance is presumably due to the formation of a stable oxide film. This subject, though discussed briefly in Chapter V of the first volume, is dealt with in detail in subsequent chapters of this volume. In addition, nickel and certain other alloying elements increase the resistance to attack by media that are reducing rather than oxidizing.

The resistance of chromium steels to oxidation at elevated temperature increases with the chromium content; the increase is most marked as the chromium exceeds 10 per cent and becomes even more rapid as the chromium passes 20 per cent. This, too, is discussed in Chapter V of Volume I and is treated in detail in subsequent chapters of this volume.

C. METALLURGICAL FUNDAMENTALS OF STAINLESS STEELS

One who first approaches the problems involved in the high-chromium steels gets the general impression that the available information constitutes a maze of complexities. Actually the behavior of the various stainless steels is not at variance with the fundamental observations of general metallurgy. As our knowledge increases, the various complex phenomena become more clearly related to common causes, and these common causes are related to our fundamental metallurgical concepts in such a way as to constitute a continuous picture.

6. The Major Concepts.—Consider the fundamentals: (*a*) Alloys that do not undergo transformation at any temperature are usually large grained, and mechanical working is the only way in which a fine grain structure may be developed. (*b*) Structures existing in a thermodynamically unstable state revert to the stable state under suitable temperature or temperature-strain conditions. Partial reversion may lead to internal stress and heterogeneity. (*c*) Single-phase alloys of iron with very large grains and polyphase alloys that undergo partial transformation frequently have low ductility. Single-phase gamma-phase alloys are an exception. (*d*) Alloys of iron generally exhibit greater ductility for a given strength as the carbon content is decreased.

To these observations, fundamental in metallurgy, add the following generalizations on alloys of iron and chromium: (1) Chromium in solid solution tends to eliminate the alpha-gamma transformation. (2) Chromium in solid solution greatly increases the time necessary for completion of any given transformation. (3) Chromium forms carbides readily, and such carbides are soluble in high-temperature austenite but almost insoluble in low-temperature austenite or ferrite. (4) Austenite-promoting elements, particularly nickel, render high-chromium steels austenitic at elevated temperatures. This austenite is thermodynamically stable at such temperatures but may be unstable at lower temperatures, some of which are sufficiently elevated to allow at least partial transformation Likewise, austenite may be supersaturated with carbon and precipitate carbides at these lower temperatures. (5) The carbon content of "eutectoid" composition of 12 per cent chromium steels is about 0.3 per cent. (6) Another phase, sigma, may appear in high-chromium iron alloys, but the alpha-sigma transformation is even more sluggish than the gamma-alpha transformation.

If we now consider the statements on high-chromium steels in the light of the fundamentals, the behavior of such alloys is logical and predictable.

7. The Plain Chromium Steels.—Essentially carbon-free alloys (irons) with more than 12 per cent chromium are relatively soft and ductile, but exposure to high temperatures results in grain growth sufficient to destroy the ductility, which cannot be restored by any heat treatment. Plain chromium steels with enough carbon to produce the austenitic phase at elevated temperatures respond to heat treatment in a manner similar to the response of plain carbon steels of much higher carbon content. With suitable carbon contents the high-chromium steels may be quenched and tempered so that their hardness ranges from that of tool steels and springs down to that of ordinary structural steels; in addition, they have greater ductility for a given strength than ordinary structural steels. They are, however, peculiarly susceptible to air hardening, and the lower ductility accompanying such hardening demands extra precautions in heating or fabricating.

High-chromium steels may readily be made hypereutectoid. Such steels correspond to hypereutectoid carbon steels in structure but have greater hardness without corresponding loss of ductility; further, the presence of chromium carbide increases their wear resistance. Such steels, in spite of much lower carbon content, must be handled and treated as tool steels, for they are sensitive to improper heating and grinding and other abuse. Because of the inherently low rate of transformation, oil quenching rather than water quenching is recommended for nearly all of the plain high-chromium steels. As the chromium and the carbon contents are increased, the alloys develop massive carbides and finally correspond to white iron in their character, except that the chromium carbides are thermodynamically more stable than the iron carbide of ordinary cast iron. If the chromium content is increased, and if the carbon content is held at a relatively low value, the iron lattice may be considered to become saturated with chromium, and under suitable temperature conditions the alloy becomes brittle owing to the appearance of sigma phase. As the chromium content exceeds 50 atomic per cent, the lattice may be thought of as that of chromium containing iron. Further increase of chromium content, to about 60 per cent, leads to the field of ferroalloys, which are used only as addition agents in the making of the chromium steels; these are discussed in Volume I.

Consider now the austenite-promoting elements. Carbon, the first and foremost of these, has already been discussed. Nickel may be used as an illustration of the metallic austenite-forming elements. When small percentages of nickel are added to ferritic low-carbon iron-chromium alloys, gamma phase may appear, and on quenching, decomposition products such as martensite are formed; they respond to tempering in the normal manner, again taking into account the general effect of chromium on the rates of reaction.

8. The Chromium-nickel Austenitic Steels.—Increasing the nickel to about 8 per cent in high-chromium alloys results in the appearance of austenite at elevated temperatures, some of which may be retained by quenching to room temperature. Thus, contrary to the result of quenching carbon steels, a relatively soft metal is produced by quenching. Tempering at about 550°C. (1020°F.) causes some of the retained austenite to change to ferrite and carbides if carbon is present; this results in the presence of internal stresses and in loss of ductility and toughness. The carbon present in the solid solution will be precipitated as a carbide, frequently at the grain boundaries, with similar effect. If the austenite changes to ferrite at some higher temperature—for example, a rolling temperature that is too low—trouble may be caused again by loss in ductility.

It is a recent view that ferrite formation may be a direct cause of carbide precipitation in the grain boundaries. This seems to be as satisfactory an explanation of the phenomenon as that in vogue for many years and still currently held. The older view involves a simpler mechanism, namely, differential solubility of carbon in austenite as a function of temperature. This implies that at the precipitation temperature, 550°C. (1020°F.) or thereabouts, only about 0.01 per cent carbon is soluble in the austenite, and that at the higher temperature from which the material is quenched for softening very much greater amounts are soluble. On quenching, these large amounts of carbon are held in solution in the austenite, and on subsequent subjection to elevated temperature or stress, or both, the supersaturated solution rejects the excess carbon in the form of carbides, generally at the grain boundaries. These carbides presumably deplete the adjacent areas of chromium. In this hypothesis there is no mention of ferrite formation, and it is postulated that the ferrite formation is purely incidental because the phenomenon of carbide precipitation may take place in alloys with relatively high nickel content, in which presumably no ferrite is formed. Both views should be kept in mind since experimentation within the next year or two will probably lead to greater clarification.

If the alpha-forming elements are increased, the tendency of austenite to change to ferrite is greater. In general, the temperature range over which austenite is thermodynamically stable is reduced, and, in fact, the temperature range over which the alloy is fully austenitic may be eliminated. This is true when chromium is increased to higher percentages without a corresponding increase of an austenite-promoting element such as nickel.

In the presence of considerable amounts of nickel, the amount of chromium necessary in the alpha-iron lattice to produce sigma phase is appreciably lower, and the rate at which this phase appears is a function of both the chromium and the nickel content. The presence of this phase also limits ductility and results in manufacturing difficulties.

9. The Chromium-manganese Austenitic Steels.—Manganese also may be used to promote the formation of austenite. However, in low-carbon steels, even at elevated temperatures, it is impossible to obtain fully austenitic material with more than 15 per cent chromium; the chromium-manganese steels are thus two-phase in character—that is, austenite and ferrite coexist at elevated temperatures and are retained as such on quenching. According to the laws of solubility, the austenite is richer in manganese and the ferrite is richer in chromium. The austenite in these steels is less stable thermodynamically than in those more fully austenitic, and partial change of the austenite, with ferrite formation on slip planes of the austenite due to certain temperature-stress conditions, seriously impairs both ductility and corrosion resistance. This is discussed in later chapters. Manganese, like nickel, tends to saturate chromium ferrite, and sigma phase occurs at much lower chromium contents. Thus the various phenomena encountered in the chromium-manganese steels are entirely in accord with the general principles.

The addition to 18 per cent chromium steels of about 4 to 6 per cent nickel and manganese in more or less equal proportions results in two-phase steels. However, the nickel in these steels stabilizes the austenite almost to the same degree as it does when present in the larger quantities common in chromium-nickel austenitic steels, so that the properties of these manganese-nickel stainless steels are similar to those of the usual 18-8 chromium-nickel steels.

10. Other Austenitic Steels.—The rôle of various other addition agents is likewise in accord with fundamental principles. Molybdenum, silicon, tungsten, columbium, and titanium are the more common of such addition elements and are all ferrite promoting. Thus, to maintain the same degree of thermodynamic stability and the same phase relations in the austenitic steels, it is necessary to add additional austenite-forming elements to counteract the effect of these ferrite-forming elements. Such additional austenitic stability may or may not be generally necessary, but there are many instances in which it is essential. Molybdenum, silicon, and tungsten provide general increase of corrosion resistance or high-temperature strength; columbium and titanium are added primarily to eliminate intergranular corrosion by "fixing" the carbon as highly persistent carbides. Thus, heating in the sensitive range is not accompanied by carbide precipitation which would produce serious impairment of physical and chemical properties.

11. Brittleness in High-chromium Steels.—A phenomenon that occurs in high-chromium steels, especially when the chromium is 20 per cent or more, is the brittleness of these materials at room temperature after they have been cooled slowly through a moderate-temperature range, the mean of which is 475°C. (885°F.). They are not brittle at 475°C. nor at any other temperature down to approximately 100°C (210°F.).

This phenomenon has not yet been explained satisfactorily; attempts have been made to correlate it with the formation of sigma phase but without success. It may be explained on the basis of precipitation, but the nature of the possible precipitate is unknown. Some metallurgists believe that it is the same as the familiar temper brittleness found in some low-alloy steels when they are cooled slowly from the tempering temperature. The authors of this monograph believe that it is a different phenomenon and prefer to call it "475°C. brittleness," a term which should describe it satisfactorily until its nature is more definitely established.

CHAPTER II

MELTING HIGH-CHROMIUM STEELS

Manufacture of High-chromium Steels with Ferrochromium—Manufacture of Low-carbon Grades with Chromium Ore—Remelting High-chromium Steel Scrap—Pouring Practice—Authors' Summary

Melting high-chromium steels is a specialized technique demanding a high degree of experience and skill and a sound knowledge of the underlying chemical reactions. This is especially true of the low-carbon high-chromium irons and the low-carbon austenitic alloys containing relatively large amounts of chromium and one or more other alloying elements. The difficulty in making ingots of these materials is caused almost entirely by the reactive character of chromium at high temperatures; in contrast to its general inertness at ordinary temperatures, chromium is very active when molten; it is readily oxidized and is oxidized preferentially to iron; moreover, it is reduced from its oxide with difficulty and has a powerful affinity for carbon. This is so great that, as discussed later in this chapter, in a molten bath containing high chromium, the usual decarburizing slag high in available iron oxide will result in a loss of chromium in the metal and an increase of this element in the slag, which may be accompanied by an actual increase of carbon in the molten bath.

Several methods of melting high-chromium steels are in general use. The first, the low-carbon ferrochromium process, is by far the most common and accounts for over 95 per cent of the world production. It consists of melting a charge of selected steel scrap in a basic electric furnace of the Héroult type and the addition to the molten bath of chromium as ferrochromium of suitable carbon content. This process commonly involves the use of selected high-chromium steel scrap which is employed jointly with ferrochromium as a source of chromium. In some instances the high-chromium steel scrap represents up to about 40 per cent of the charge, while in others even larger percentages of scrap are used. In the second, the chromium ore process, a charge of selected scrap is melted; chromium ore is added to the slag, the chromium is reduced from the oxide by silicon and passes into the metal bath. In addition to these two methods, a third has been described by Becket* and by Feild(266) for producing low-carbon high-chromium alloys by melting a charge of selected steel scrap, adding chromium as the high-carbon ferroalloy, decarburizing the bath, and deoxidizing the slag after the chromium is added. The use of the open hearth for scrap remelting might be listed as a fourth method, but it is so new, and the total tonnage production is so small, that many would still consider it as experimental. High-chromium scrap is melted in a specially designed open-hearth furnace or in an electric furnace; conditions in the furnace are so controlled that oxidation of the chromium in the scrap is prevented so far as possible.

A. MANUFACTURE OF HIGH-CHROMIUM STEELS WITH FERROCHROMIUM

A pithy statement, made some years ago by Smith,(245) concerning the manufacture of high-chromium steels represents the experience of an operating man and is as apropos now as it was then:

> Making a heat of stainless to the proper chemical composition is largely a matter of good weighing. Making a heat of stainless of proper metallurgical characteristics is an art, and putting the product from the electric furnace all the way through to the customer is an accomplishment.

12. Melting Medium- and High-carbon High-chromium Steel in the Electric-arc Furnace.—In general, the melting practice for the high-chromium cutlery and tool or die steels is not so difficult as that for the low-carbon grades; consequently, the emphasis in this chapter is on the latter. For the medium- and especially for the high-carbon high-chromium materials, ferrochromium containing considerable carbon may be used.† Thus, if it is desired to make an 18,000-lb. heat of cutlery steel containing 0.30 per cent carbon and 13.5 per cent chromium,

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* U. S. Patent 1,897,017, issued February, 1933.

† Analyses of the various grades of ferrochromium are given on p. 20 of the first volume of this monograph.

3470 lb. of 70 per cent ferrochromium will be required. If the bath contains 0.05 per cent carbon after melting, about 2000 lb. of 2 per cent carbon ferrochromium and 1470 lb. of 0.5 per cent carbon ferrochromium may be used. As the cost of ferrochromium varies inversely with the carbon content, furnacemen generally melt the heat with a relatively low carbon so that cheaper grades of ferrochromium may be used.

With the higher carbon varieties of stainless steel, carbon may be used in the deoxidizing slag. It is generally considered that basic electric steels deoxidized with a carbide slag are sounder and freer from inclusions than those deoxidized with the white disintegrating type of slag, which must be used for the low-carbon high-chromium steels so that there will be no carbon pickup by the bath. In this connection a statement by Feild(266) is significant:

> When a certain carbon content is permissible (as in the cutlery steels) it is good practice to employ a certain amount of pulverized coke to assist in shaping up the finishing slag, and the carbide slag may be built up and with judgment maintained.

13. Melting Low-carbon High-chromium Steel in the Electric-arc Furnace.—A large proportion of the tonnage of low-carbon high-chromium steels produced is melted in the basic arc furnace from a charge of low-carbon low-phosphorus steel scrap or, occasionally, in the case of the 18-8 material, from low-carbon low-phosphorus nickel steel or nickel-chromium steel scrap. This practice has been described in considerable detail by a number of workers in the field(143,191,245,266,316,406) and is, consequently, well known. Essentially, the process consists of melting a charge, usually 12,000 to 25,000 lb. of scrap, using a black slag of lime, iron ore or roll scale (200 to 500 lb. per heat), and fluorspar, if necessary. When the charge is molten and oxidation has been carried to the extent desired, the black slag is removed as completely as possible. The carbon in the molten metal should be 0.04 per cent or less.

The final slag is of the "white" disintegrating type and is composed of lime, fluorspar, and ferrosilicon (50 per cent or more silicon) in the approximate proportions of 7:3:2. These proportions vary somewhat, depending upon the composition of the steel and upon the conditions in the furnace. There is practically no carbon pickup from this slag, which is composed essentially of calcium orthosilicate ($2CaO.SiO_2$) and contains 60 to 65 per cent CaO. Upon cooling, it disintegrates to a fine white powder because of a marked volume change in the crystal form of the silicate at 650°C. (1200°F.).

It is important to use dry raw materials in melting the low-carbon high-chromium steels. When wet or damp materials are used the moisture dissociates under the influence of the arcs into oxygen and hydrogen. The oxygen forms an oxide with the chromium in the bath, while the hydrogen dissolves and causes a gassy condition. If too much silicon is added to the bath during melting, a gassy condition will also develop, although the reason for this is not clear. Normally the silicon content during melting is kept well below 0.30 per cent to avoid this.

14. The Deoxidation of Low-carbon High-chromium Steels in the Arc Furnace.—As carbon cannot be added to the final slag, such deoxidation as occurs previous to the manganese and silicon additions is through the agency of powdered ferrosilicon or a special iron-silicon alloy containing zirconium or other deoxidizer, added to the slag. Ferrosilicon has a low specific gravity; when finely divided, it is held in suspension in the slag and serves to reduce the oxides present in the slag or at the slag-metal interface. A partial deoxidation of the metal bath is thus attained. The final deoxidation is made with low-carbon ferromanganese and ferrosilicon. It is not uncommon to add about 0.1 per cent calcium as a calcium-silicon alloy to the high chromium-nickel alloys just before tapping. Aluminum, barium-silicon, and magnesium have also been used. According to Feild,(266) the addition of magnesium is necessary to obtain satisfactory hot-working properties; its function "in these high-nickel [18-8] alloys is related to sulphur rather than to oxygen." Calcium, however, is a more common addition than magnesium.

Judging the temperature of the molten metal is difficult, as high-chromium steels are thick and sluggish and give the appearance of being much colder than they really are. Chromium does not affect the freezing point of iron appreciably; a 25 per cent chromium iron-chromium alloy freezes at a temperature only some 25 to 30°C. (45 to 55°F.) lower than high-purity iron. Carbon does not affect the freezing point of iron-chromium alloys to any greater extent than it affects the freezing point of iron: a high-chromium steel containing 0.10 per cent carbon freezes at approximately the same temperature as an unalloyed open-hearth steel of the same carbon content.

Because of the large quantities of alloy additions to the molten bath—an 18,000-lb. heat of 18-8 includes 5000 to 6000 lb. of ferrochromium and nickel—temperature control during the deoxidizing period is very important. The bath must be superheated before the alloying elements are added, and in most cases they are added in two or three batches, the bath being heated between the additions. Gatti(316) recommended preheating the ferrochromium to about 850°C. (1560°F.) before adding it to the furnace. Great care must be exercised during superheating to avoid direct contact between the electrodes and the bath as the latter will absorb carbon rapidly. Siegel(509) has shown by a study of energy consumption versus temperature in the basic arc furnace that preheating the ferrochromium aids deoxidation. If the alloy is thoroughly preheated, deoxidation proceeds continually from the time of the ferroalloy addition until the heat is tapped. If, however, the alloy is added cold, deoxidation slows down and may even stop; there is, strictly speaking, no real cleansing of the molten metal, and the time between the ferroalloy addition and tapping is spent in heating the metal to the proper temperature. The effect of preheating the ferrochromium is clearly evident in the ingot structure.

After the alloying additions have been made and melted, the bath is stirred, and samples are taken for judging temperature; these are also used for chemical analysis if this is necessary. Final small additions of ferrochromium and nickel are made if adjustments in composition are required; ferromanganese and ferrosilicon are then added; the temperature is adjusted, and, if advisable, calcium-silicon or another alloy is added as a final deoxidizer; then the heat is tapped. According to Houdremont,(143) ferrochromium should not be added until the bath is completely deoxidized by the slag and by ferromanganese and a portion of the ferrosilicon. The remainder of the ferrosilicon is then added just before tapping.

The addition of nickel to low-carbon high-chromium steels has little or no effect on the melting practice. As mentioned in a previous monograph,(503) nickel is not oxidized preferentially to iron; it may, therefore, be added at any time. In many plants most of it is charged, as electrolytic nickel or as nickel scrap, with the rest of the scrap at the beginning of the heat.

Frequently other alloying elements are added to stainless steel. Molybdenum, cobalt, and copper are introduced early in the heat and present no very great problems, but such elements as columbium, titanium, aluminum, and silicon oxidize even more readily than chromium and must be added at the very end of the heat. Details on these additions are given in later chapters. Nitrogen is used in some grades of stainless steels; this is discussed at greater length in the next section.

15. Steels Made with High-nitrogen Ferrochromium.—Nitrogen additions are in general beneficial to high-chromium steels. Data summarized in a later chapter indicate that nitrogen refines the grain and improves toughness without reducing corrosion resistance. The element is added in the form of high-nitrogen ferrochromium containing about 0.70 per cent nitrogen and 70 per cent chromium with carbon contents of 0.2 per cent or more. Depending upon the chromium content in the steel, which ranges between 12 and 30 per cent, the nitrogen content may vary between 0.08 and 0.25 per cent. Nitrogen is now widely used in the United States for the ferritic steels containing about 25 per cent chromium.

The high-nitrogen ferrochromium is employed in the same manner as the ordinary ferrochromium. Approximately the same recovery of chromium is obtained, and at least 90 per cent of the nitrogen added is retained in the finished product. If low- and high-nitrogen ferrochromium are used in the same charge to obtain an intermediate nitrogen content, it is advisable to add the low-nitrogen ferrochromium first. This permits closer control of the desired nitrogen content of the finished steel.

The affinity of iron-chromium alloys for nitrogen is important. It is probable that relatively stable chromium nitrides are formed. Thus, even if no ferrochromium high in nitrogen is added to the bath, the final metal will contain appreciably more nitrogen than a similar steel containing no chromium. The amount of nitrogen pickup in melting varies with the melting practice, the type of furnace, and the like, and no general figure can be given. However, for many grades of high-chromium steels this increase in nitrogen may be an important factor, and it should be given due consideration by the melter.

16. Recent American Electric-furnace Practice for Low-carbon High-chromium and Chromium-nickel Steels.—Published details on electric melting practice for low-carbon high-chromium and for 18 per cent chromium, 8 per cent nickel steels are rare; for that reason, and because complete logs of two typical heats are given, the recent paper by Farnsworth and Johnson(492) is quoted in considerable detail.

The heats described were melted in a basic arc furnace of the Héroult type with a nominal capacity of 15 tons. The usual lining of silica brick above the slag line and the usual roof, also of silica brick, were used. The bottom was of magnesite brick; but a special procedure was used in putting in the working hearth. Instead of dolomite, a mixture of 80 per cent periclase grain (90 per cent magnesium oxide), ranging from ½- down to ⅛-in. mesh or smaller, and 20 per cent finely ground dead-burned Austrian magnesite was used. To this, sodium silicate was added as a binder. The plastic refractory was rammed in in layers 2 to 3 in thick until the required thickness and contour were obtained. The hearth was then thoroughly dried with a wood fire and burned in at a very high temperature.

All raw materials including scrap, ferroalloys, and lime, fluorspar, sand, and coke for the slag were carefully selected for both physical condition and chemical composition.

> The condition of the scrap is very important . . . as it can influence the quality of the finished product . . . Every effort is made to keep these [slag-making] materials dry, as the presence of moisture can be very troublesome.

The melting practice as outlined by Farnsworth and Johnson was as follows:

> The furnace is charged first with selected heavy scrap and then with the lighter scrap. In the case of high-nickel steels, a large portion of the nickel is charged along with the scrap. The placing of the scrap in the furnace and the proper proportion of light and heavy scrap are important from the standpoint of bottom difficulties and rapid melting. Sufficient carbon, in the form of anthracite coal or ground carbon electrode, is charged in with the scrap, so as to produce a vigorous boil with the addition of iron ore. The charging of a large amount of lime or limestone with the scrap will retard melting. It is preferable to shovel in burned lime during the melting. The melting is done as rapidly as

possible. High voltage is used for the first hour and a half of melting. Since the high voltage throws a large arc and would damage the side walls and roof after the scrap is under cover, the intermediate voltage is used when partly melted and low voltage when completely melted. In the case of molybdenum steel, calcium-molybdenum is added during the melting. Ore is added in the furnace just before and just after the scrap is completely melted. When the charge has completely melted and the boiling action from the ore has subsided, tests are taken for analysis. The carbon is determined quickly by means of a carbometer, after which the making of the heat progresses while the chemical laboratory analyzes other elements, such as manganese, nickel, molybdenum, etc. Since the scrap charge is of known composition, there is little chance of these elements not being within the desired limit, or in such amounts that they cannot be brought within the specification. So, when the carbon is oxidized to a desired point, the oxidizing slag is removed.

The need for extra care in making stainless steel, particularly to avoid possible hydrogen absorption, is stressed by Farnsworth and Johnson. Such hydrogen may come from moist materials or from sources such as the atmosphere. The lower chromium low-carbon steels seem to be even more susceptible than those of very high chromium content. The following quotation from Farnsworth and Johnson describes representative practice:

> The slag conditions have a very decided effect. The metal is not so susceptible to the effects of hydrogen when made under a carbide slag or a slag containing some oxides. Therefore, with some grades and under certain conditions, a white lime-silica slag is very dangerous. However, such slag should not be confused with one that is produced with coke additions without any appreciable carbide present.
>
> It is always desirable from the standpoints of oxidation loss, close analysis control and good furnace practice to finish the heat under a slag relatively free from oxides. Since carbon cannot be used, other reducing agents such as silicon or aluminum are used, and of these silicon is the most common reducing agent added.
>
> Lime-silica and lime-alumina slags, when properly shaped up, will disintegrate to a white powder when cooled.
>
> A typical analysis of a lime-silica slag is [shown in the table on page 23].
>
> In producing the stainless steels with a chromium content of over 16 per cent from a common scrap charge, a white lime-silica slag may safely be used if reasonable care is taken to avoid the presence of

Constituent	Percentage
CaO	60 72
SiO_2	26.22
Al_2O_3	2 30
FeO	0.76
MgO	5 42
P	0 01
S	0.97
Cr_2O_3	0 33

> moisture, as mentioned [before]. Except with respect to alloy additions, the furnace practice is much the same on all of the grades containing over 16 per cent of chromium when made from a common scrap charge. With the chromium-nickel stainless grades, a large portion of the nickel is added with the scrap charge. The charge is melted with additions of lime and sufficient iron ore to oxidize the carbon to below 0.03 per cent. When completely melted, tests are taken for analysis and the oxidizing slag is raked off clean. The finishing slag mix, consisting of lime, crushed ferrosilicon (75 per cent silicon) and fluorspar, is then added. The lime-silicon ratio in the slag mix should be about two and one half units of lime to one of silicon. To reduce the excess oxides and form a white slag, silicon amounting to 0.50 per cent of the scrap charge is usually sufficient. When the white slag is formed, tests are again taken for analysis, and preheated ferrochromium is then added. The lowest carbon content obtainable in the commercial grades of ferrochromium is 0.06 per cent maximum, and this is used when a carbon content of under 0.07 per cent is to be maintained in the finished heat.
>
> The original scrap charge and all additions are accurately weighed, so that it will not be necessary to run an analysis after the chromium addition is made. It is important that the additions be made at intervals and in amounts that will not cause the temperature of the metal bath to drop too low. In calculating the additions, no allowance is made for the oxidation loss of chromium or manganese when the heat is made under a white lime slag. However, some allowance must be made for the silicon losses.

Details are given in Table 1.

The problem of remelting stainless-steel scrap is important and is described as follows:

> Ordinarily common scrap may be melted in the arc furnace with no noticeable carbon pick-up in the metal bath from the electrodes. If some carbon is absorbed, there is usually sufficient oxide on the surface of the scrap to oxidize it out. Scrap containing a high percentage of chromium has a greater affinity for carbon and it is not so easily oxi-

TABLE 1.—LOG OF 15-TON BASIC-ELECTRIC HEAT OF LOW-CARBON 18 PER CENT CHROMIUM, 8 PER CENT NICKEL STEEL*

Analysis	C	Mn	Si	S	P	Cr	Ni
Ordered	0.07 max.	0.40 to 0.60	0.30 to 0.50	0.025 max.	0.025 max.	17.50 to 18.50	8.75 to 9.25
Ladle test	0.057	0.44	0.41	0.011	0.015	17.94	8.93

Time	Additions	Remarks	Analysis of metal, per cent		
			C	P	Ni
10:35 A.M.		Previous heat tapped			
10:45 A.M.	24,000 lb. common scrap and 3100 lb. nickel	Began charging			
11:05 A.M.		Current on high voltage (220 V)			
11:45 A.M.	300 lb. lime	Current on intermediate voltage (170 V)			
12:20 P.M.	200 lb. lime	Current on low voltage (110 V)			
12:30 P.M.	400 lb. iron ore				
12.45 P.M.		Bath stirred	0.03		
12.50 P.M.		Began slagging			
1:00 P.M.		First slag completely removed			
1:10 P.M.	500 lb. lime, 175 lb. crushed silicon, 50 lb. fluorspar	First test taken for analysis			
1:30 P.M.			0.027	0.016	11.40
1.50 P.M.	230 lb. nickel				
2:10 P.M.		Bath stirred. Temperature tested			
2:45 P.M.	3090 lb. ferrochromium	0.06 % C, 71.58 % Cr, 0.72 % Si (ferrochromium)			
3.10 P.M.		Bath stirred. Temperature tested			
3:20 P.M.	140 lb. ferromanganese	0.06 % C, 82.00 % Mn (ferromanganese)			
3:25 P.M.	150 lb. lime, 50 lb. crushed silicon (76 % Si)				
3:35 P.M.	122 lb. lump silicon (76 % Si)				
3.50 P.M.		Bath stirred. Temperature tested			
4:00 P.M.		Heat tapped			

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* Farnsworth and Johnson (492)

dized. Additions of iron ore will oxidize considerable chromium before any of the carbon is eliminated. The carbon is usually absorbed in the first stages of melting, when the movement of the electrodes is down through the scrap and until a pool of metal has been formed. After the pool of metal is formed and is protected with a slag covering, there is little or no danger of further carbon pick-up. Various methods of melting stainless scrap to avoid carbon pick-up have been developed, all of which require most careful control, and some are questionable economy.

With proper control, it is possible to reclaim a large percentage of stainless scrap with a 0.12 per cent maximum carbon limit, but to maintain a carbon content of under 0.07 per cent in the finished heat is more difficult. The induction furnace is used as an aid in reclaiming the lower carbon scrap. In maintaining a carbon content of 0.12 per cent in the finished heat, stainless scrap amounting to approximately 50 per cent of the total charge is melted in conjunction with ingot-iron scrap, which has a carbon content of 0.03 per cent. The ingot-iron scrap is obtained from mill crop-ends produced in the authors' own plant. In order to avoid an excessive carbon pick-up, certain precautions are essential in the charging and melting. The ingot-iron scrap is charged first directly under the electrodes. Iron ore, amounting to from 1 per cent to 2 per cent of the total charge, is placed on top of the ingot iron. Heavy stainless mill crops and ingot butts are placed around the sides so as not to come in contact with the electrodes, and light stainless scrap is distributed over the top of the charge The melting is started with high-voltage current adjusted to about one-half of the full load capacity, which provides a long arc and prevents as nearly as possible close contact between the scrap and electrodes. As the charge melts, a slag mix consisting of lime, sand and fluorspar, is added to provide a fluid slag covering as soon as a pool of metal is formed beneath the electrodes. When completely melted, crushed silicon and lime are added to reduce the oxides that have formed in the slag during melting. Tests are then taken for analysis, after which part of the slag volume is removed. The amount of silicon used will not reduce the oxides completely, but it is sufficient to cause a small amount of residual silicon in the metal bath. A white lime slag is dangerous from the standpoint of hydrogen absorption in stainless-scrap heats. Since the scrap charge is of known composition, the major portion of the preheated chromium is added before the laboratory results are obtained. Thereafter, only small adjustments are necessary to bring the metal bath within the desired specifications.

The log of a heat of stainless steel made in an arc furnace with stainless-scrap additions is recorded in Table [2].

TABLE 2.—LOG OF 15-TON BASIC-ELECTRIC HEAT OF 17 PER CENT CHROMIUM STEEL*

Analysis	C	Mn	Si	S	P	Cr
Ordered	0.10 max.	0.30 to 0.50	0.30 to 0.50	0.025 max.	0.025 max.	16.50 to 17.50
Ladle test	0.086	0.43	0.43	0.012	0.016	17.30

Time	Additions	Remarks	Analysis of metal, per cent			
			C	Mn	Si	Cr
8:10 A.M.		Previous heat tapped				
8:20 A.M.	13,000 lb. ingot-iron scrap (0.03 % C), 19,000 lb. stainless scrap, 400 lb. iron ore	Began charging. 0.09 % C, 17.20 % Cr in stainless scrap				
8:50 A.M.		Current on high voltage				
9:05 A.M.	300 lb. lime, 100 lb. fluorspar, 100 lb. sand					
9:50 A.M.	300 lb. lime, 100 lb. fluorspar, 100 lb. sand	Current on intermediate voltage				
10:25 A.M.		Current on low voltage				
10:40 A.M.		Bath stirred				
10:45 A.M.	150 lb. crushed silicon (75 % Si)					
10:55 A.M.		Bath stirred				
11:00 A.M.		First test taken for analysis				
11:10 A.M.		Began slagging				
11:20 A.M.		Finished slagging; one-half to two-thirds of slag removed				
11:25 A.M.	300 lb. lime					
11.30 A.M.	2500 lb. ferrochromium	0.20 % C, 70.20 % Cr (ferrochromium)				
11:40 A.M.			0.07	0.25	0.08	0.03
12:00	2500 lb. ferrochromium	0.20 % C, 70.20 % Cr (ferrochromium)				
12.30 P.M.		Bath stirred. Temperature tested				
12:40 P.M.	150 lb. lime, 50 lb. crushed silicon (75 % Si)					
12:55 P.M.	95 lb. ferromanganese	0.60 % C, 82.00 % Mn (ferromanganese)				
1:10 P.M.		Bath stirred. Temperature tested				
1:20 P.M.		Heat tapped. 190 lb. calcium-silicon alloy (62 % Si) added to ladle				

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* Farnsworth and Johnson.(492)

Farnsworth and Johnson also described a duplex process involving induction- and arc-furnace use. They reported reclamation without difficulty of stainless-steel scrap with carbon under 0.07 per cent.

17. Russian Practice Using Ferrochromium.—As the result of experimental work on a large number of heats of low-carbon 16 to 18 per cent chromium iron and low-carbon 18 per cent chromium, 8 per cent nickel steel, a standard practice was worked out for Russian mills melting stainless steels. The practice was applied to a test run of 150 heats all of which contained less than 0.12 per cent carbon and were within the required specifications for other elements; moreover, all were reported to be sound and to have very satisfactory properties. This standard practice has been published(406) and contains many points of interest. For a low-carbon high-chromium steel, the charge contains 8400 kg. (18,500 lb.) of carbon-steel scrap of known analysis, 400 kg. (900 lb.) of charcoal pig iron, and 200 kg. (450 lb.) of ferromanganese. For an 18-8 heat, the scrap is reduced to 7400 kg. (16,300 lb.), and 1000 kg. (2200 lb.) of nickel is included in the charge. The 9000-kg. (19,800 lb.) charge is balanced so that it will melt with 0.55 to 0.60 per cent carbon and 1.0 to 1.2 per cent manganese. Special precautions are taken to ensure that all materials charged are dry.

The voltage is carefully regulated during melting, and lime is added at specified intervals. As soon as the charge is entirely melted, a specimen is taken for analysis, and iron ore is added in small lots, frequently spaced to ensure a continuous boil. The carbon should be reduced from about 0.60 per cent to not less than 0.15 per cent in 1 hr. During this period, the bath is kept at a temperature high enough so that the metal will flow readily from a test spoon. When the carbon is lowered to 0.06 or 0.07 per cent, no more ore is added. By the time the boil ceases, the carbon is 0.04 per cent. All during the oxidizing period, small amounts of ferromanganese are added so that the manganese content will not fall below 0.20 per cent. Near the end of the boil, manganese metal is substituted for the ferroalloy. The percentage of manganese in the bath is estimated by analyses and checked by forging tests.

After the oxidizing slag is removed, aluminum equivalent to 0.1 per cent of the charge, and 75 per cent ferrosilicon equivalent to 0.15 per cent silicon in the charge are *added; also*, enough manganese metal is added to bring this element up to 0.50 per cent. The deoxidizing slag consists of lime and fluorspar in the proportion of 5:1. After this has been put in the furnace (in an amount equivalent to 4 per cent of the charge) and has melted, a mixture of 1 part powdered ferrosilicon and 2 parts lime is added in small portions until the metal lies quietly in the test spoon. Then low-carbon ferrochromium, preheated to about 700°C. (1290°F.), is added in three equal portions. During this addition the electrodes are raised clear of the bath. Following the addition of the last portion of ferrochromium, further additions of the ferrosilicon-lime mixture are made. This completes the deoxidation of the slag and also introduces the remainder of the required silicon into the bath. The instructions published by Speransky(406) give minute directions for controlling a 10-ton heat as well as for casting the metal; 9.5 hr. from tap to tap is given as average.

18. Peculiarities in the Chemistry of Melting and Deoxidizing Low-carbon High-chromium Steels.—A broad outline of the chemistry of melting and deoxidizing low-carbon stainless steels from low-carbon scrap is given in sections 13 and 14, where it is stated that the primary reagent for deoxidizing is silicon added to a white slag. The manufacture of these high-chromium steels presents some unique conditions in melting and refining which receive attention in the present section,conditions that are related directly to the high affinity of molten chromium for carbon and which make it exceedingly difficult to decarburize a molten bath containing chromium. Chromium not only combines with the carbon in the molten metal to form a very stable carbide, but also forms a carbide when in contact with carbonaceous gases. Little work has been done on this phase of the chemistry of melting these materials and less has been published, but it is well known that if the bath contains high chromium, any attempt to decarburize it with a slag containing iron oxide results in oxidation of chromium, which passes from metal to slag.

In some cases this oxidation of the chromium is accompanied by an increase in the carbon in the metal bath. This does not always follow, however, as the removal of carbon from 0.10 to as low as 0.03 per cent has been obtained* while maintaining 3.5

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* Private communication, C. E. Williams, Battelle Memorial Institute, Dec 14, 1938.

to 5 per cent chromium in the slag. This oxidation of the carbon was accompanied by the following changes in the chromium content:

Furnace condition	Chromium in metal, per cent	Slag, per cent	
		Cr_2O_3	FeO
Before addition of iron ore	7.55	10.13	6.52
After addition of iron ore	4.36	22.60	9.52

These results indicate that the behavior of the carbon depends upon slag and temperature conditions.

According to Forsyth,(359) the dissociation of chromium oxide (Cr_2O_3) into chromium and oxygen takes place only to a very small extent at high temperatures as compared with the dissociation of ferrous oxide (FeO) under comparable conditions. As a result, the gaseous phase in equilibrium with the system

$$Cr_2O_3 + 3C \rightleftharpoons 2Cr + 3CO \tag{1}$$

is very much higher in carbon monoxide than for a similar reduction of ferrous oxide by carbon. The reactions

$$3Cr_2O_3 + 13CO \rightleftharpoons 2Cr_3C + 11CO_2 \tag{2}$$
$$3Cr + 2CO \rightleftharpoons Cr_3C + CO_2 \tag{3}$$

can proceed from left to right only when the concentration of carbon monoxide in the gas phase is below that in equilibrium with equation (1).

Forsyth stated that as the result of reactions (1), (2), and (3) a carburized bath containing chromium can be decarburized with minimum oxidation of the chromium only when the oxidizing agent has an oxygen concentration equal to that of chromium oxide. It has been found(263) that this is in accordance with practice; high-chromium steel is decarburized more effectively using a slag containing Cr_2O_3 than one containing FeO. With the latter, chromium oxidizes more rapidly than iron or carbon. Silicon, oxidized very rapidly by the usual black FeO slag, is oxidized very slowly by the oxidizing slag containing Cr_2O_3.

B. MANUFACTURE OF LOW-CARBON GRADES WITH CHROMIUM ORE

Owing to the cost of low-carbon ferrochromium, efforts have been made to manufacture low-carbon high-chromium steels from chromium ore. Briefly, the process consists of melting a charge of low-carbon low-phosphorus steel scrap in a basic-electric furnace and removing as much carbon as possible. This is followed by adding a slag consisting of the proper proportions of chromium ore to give the required amount of chromium in the metal and reducing the chromium from its oxide by silicon. In addition to the large slag volumes that must be handled, there are a number of other problems to be solved. There are two processes that involve the use of chromium ore, both of which have been patented.* Little has been published on either of the processess; there are a few sketchy details given by Feild$^{(266)}$ on the Wild process and by Monypenny$^{(191)}$ on the Hamilton-Evans process.

19. The Wild Process.—Essentially, the Wild process consists of melting low-carbon low-phosphorus scrap in the usual manner, oxidizing as much carbon as possible, and removing the black slag completely. Additions of chromium ore and ferrosilicon are then charged into the furnace, using an excess of ore to prevent too much silicon from going into the bath. The slag formed is removed from time to time.

According to Arness,† the current melting practice involves the remelting of stainless-steel scrap plus the reduction of chromium ore. In melting, much of the chromium in the scrap is, of course, oxidized and passes into the slag. This chromium oxide plus the chromium oxide added as chromium ore is reduced with ferrosilicon. The reactions involved are:

$$2Cr_2O_3 + 3Si \rightleftharpoons 4Cr + 3SiO_2 \qquad (4)$$

$$2FeO + Si \rightleftharpoons 2Fe + SiO_2 \qquad (5)$$

When these reactions are completed, the reduction slag is removed and samples are taken for chemical analysis. The heat is finished under a white slag which is deoxidized by ferrosilicon as described in section 14. Low-carbon ferrochromium is then added if necessary, followed by the usual amounts of ferromanganese and ferrosilicon, and the heat is tapped. Some details of this process have also been given by Monypenny.(191)

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* Hamilton-Evans process: British Patents 174,271; 198,323; 211,210; 213,737; and 262,206; Wild process: British Patent 198,423; U. S. Patents 1,925,182 and 1,954,400.

† W. B. Arness, private communication, Mar. 24, 1938.

20. The Hamilton-Evans Process.—As described by Monypenny(191) and Forsyth,(359) the Hamilton-Evans process makes use of a so-called "receptor" slag which, according to Forsyth, probably contains about 35 per cent CaO, 20 per cent MgO, 20 per cent SiO_2, 3 to 4 per cent FeO + Fe_2O_3, 4 to 6 per cent Cr_2O_3, and about 15 per cent Al_2O_3. This slag is added to the furnace after the initial oxidizing slag has been removed. When the receptor slag is in "good shape," the temperature is increased and a mixture of chromite and ferrosilicon is added. Chromium is reduced and goes into the metal. The loss in chromium is about 25 per cent of that charged, and the efficiency of the ferrosilicon used for reducing the chromium oxide is around 65 per cent. It has been stated(143) that by the reduction of chromite by the reaction

$$FeO.Cr_2O_3 + 2Si = Fe.Cr_2 + 2SiO_2 \qquad (6)$$

not more than 13 per cent chromium can be obtained in the bath.

21. Variants of the Chromium-ore Process.—Several variations of the processes just mentioned have been outlined briefly in the literature. Houdremont(143) described the manufacture of high-chromium steel in a basic open-hearth furnace using pig iron, scrap, chromium ore, and ferrosilicon as the charge.

Lippert(466) recently outlined the manufacture of high-chromium steel for castings in an electric furnace of the direct-arc, single-phase type, with two rotating 10-in. graphite electrodes having a 4.5-in. diameter hole. The electrodes projected through the ends of the furnace at a slight angle to the horizontal. The bath was not a part of the arc circuit. The chromium ore was charged in the form of briquettes, 3 in. long and about 4 in. in diameter, made from a mixture of 100 lb. of ore, 14 lb. of coke, and 3 lb. of a binder. The arcing electrodes melted the 2000-lb. charge of steel scrap, after which the ore-coke briquettes were fed through the rotating hollow electrodes. According to Lippert, the result is reduction of the chromium oxide, an increasing chromium content of the bath, and a simultaneous oxidation of carbon, silicon, and manganese. As the bath temperature is high, about 1870°C. (3400°F.), special refractories must be used. For a 2000-lb. heat of low-carbon high-chromium steel the melting time was about 3 hr. and the power consumption about 1000 kw-hr. per ton.

22. Forsyth's Investigation of the Chromium-ore Process.—Forsyth(359) studied the chemical reactions and the general efficiency of the use of chromium ore as a source of chromium for low-carbon high-chromium steels. His study was made on laboratory heats, and he used a small indirect-arc furnace so that his data, especially for the economics of the process, are probably not comparable with the operation of a direct-arc furnace melting a 6- to 10-ton charge. The charge was low-carbon iron; the receptor slag was mixed and added in portions after the iron was melted, and each portion was allowed to become completely liquid before the next one was added. The slag was thinned with fluorspar and the chromite-ferrosilicon mixture was added, also in portions, the furnace being sealed between additions. The analyses of a typical receptor slag and of a final slag were as follows:

Constituent	Percentage	
	Receptor slag	Final slag
CaO	35.1	23.1
MgO	21.4	26.0
SiO_2	17.6	28.2
Al_2O_3	16.4	17.3
Cr_2O_3	4.4	2.3
FeO	4.0	1.4
MnO	0.30	0.26

The finished ingot contained 0.26 per cent carbon, 12.2 per cent chromium, 0.60 per cent silicon, and 0.14 per cent manganese.

From the results obtained with a number of these small heats Forsyth concluded that low temperatures favor the reduction of chromium oxide. This would be challenged by most metallurgists and directly contradicts the principle of the hollow-electrode furnace. The efficiency of ferrosilicon in reducing the chromium oxide of the chromite varied from 75 to 81 per cent. The slags were bulky; they weighed about as much as the metal. Forsyth believes that the chromium oxide content of the receptor slag should be around 10 per cent. The final slag is low enough in iron oxide so that it corresponds in analysis for FeO to the usual white slag. Despite the fact that the heavy slag was not removed before pouring, the ingots were reported to be sound and free from inclusions. Trouble was encountered in keeping the carbon of the melts low enough.

Forsyth also studied power consumption and the thermal efficiency of the process, but as he based his reasoning on the results for small heats, extrapolation to an industrial scale required many assumptions.

C. REMELTING HIGH-CHROMIUM STEEL SCRAP

During the processing of low-carbon high-chromium and chromium-nickel steels a large amount of scrap is produced, considerably more than is usual with comparable processing of carbon or low-alloy steels. It is important, because of the value of the alloying constituents contained in these steels, that the scrap be remelted with a minimum loss in chromium and with no great increase in carbon content. A special technique is required to use the arc furnace to remelt charges consisting entirely of chromium-steel scrap without excessive carbon pickup or chromium losses; it is, however, quite suitable for remelting a mixture of chromium-steel and low-carbon steel scrap. The latter procedure has been described recently by Farnsworth and Johnson(492) (see section 16).

This process, however, does not permit utilization of all the chromium or chromium-nickel scrap usually available; hence, experiments have been made and procedures have been worked out to remelt charges consisting entirely of this scrap in (1) the induction furnace, (2) the electric-arc furnace, and (3) small open-hearth furnaces. These are considered in order.

23. Melting Chromium-steel Scrap in the Induction Furnace. The induction furnace, of either high or low frequency, is a practical medium in which to remelt high-chromium scrap with low oxidation loss of chromium and no increase in carbon; a number of plants, both in the United States and abroad, have installed such equipment. The use of a low-frequency furnace of the Röchling-Rodenhauser type of nominal 6-ton capacity, rated at 800 kw., has been described by Smith,(245) Feild,(266) Gatti,(316) and, recently, by Farnsworth and Johnson.(402) Charging is done by hand, and the furnace taps about 9500 lb. of metal every 3 hr. (about 3000 lb. of molten metal is left in the furnace as a basis for the next heat). A detailed description of this furnace and the method and economics of its operation is readily available.(245,492) Smith(245) reported that the conversion cost of melting by this method is about the same as in the arc furnace; the more expensive bottom of the low-frequency furnace and the extra cost of hand charging just about balance electrode cost in the direct-arc furnace. The slag volume is low, and temperatures are more difficult to judge, but in the low- (and the high-) frequency furnaces, oxidation can be held to an inconsequential amount, and the convection currents induced within the molten metal promote uniformity.

High-frequency furnaces of the Ajax-Northrup type with capacities up to 4 tons have been installed for remelting low-carbon high-chromium scrap. It is claimed that this furnace is easier to maintain and more flexible in operation than the low-frequency furnace. In contrast to the latter, the charge in the high-frequency furnace is completely tapped. Either type of furnace may be used for melting in a special atmosphere.

24. Melting Chromium-steel Scrap in the Arc Furnace.—Although it requires considerable skill, a charge consisting mostly of stainless-steel scrap may be remelted in an arc furnace and the carbon content may be maintained at 0.10 per cent or less. The procedure starts with the production of a small bath of low-carbon iron; this is done by the usual methods. Slag volume sufficient for a full charge is then added, using the usual lime-silica slag; this is kept deoxidized with a small amount of manganese, as well as ferrosilicon or other agents. The high-chromium steel scrap is then charged into the slag cover, care being taken to avoid direct contact with the graphite electrodes. These electrodes are operated at higher voltage than usual with the object of getting a long arc; 140 volts or more may be used, the limitation being the temperature attained by the roof bricks. The scrap is charged in relatively small batches, and the slag is kept light green in color by means of ferrosilicon-zirconium or ferrosilicon additions. This reduces the viscosity of the slag which, thus, readily coats the relatively light stainless scrap. After all the stainless-steel scrap has been added, a final manganese addition is made, and final shaping of the slag is followed by a small low-carbon ferrochromium addition for adjustment of analysis. The hêat is then finished and tapped in the usual way.

Another method of handling stainless-steel scrap in the arc furnace involves combination with the direct-process operation. The stainless scrap is in the initial charge, and a portion of its chromium content is allowed to oxidize and form a high-chromium slag. This is then treated with other chromium oxide additions in the manner described in section 19. The use of stainless scrap in this way is an advantageous factor in the cost of production of stainless ingots by the direct process.

A third variant of handling stainless-steel scrap in the arc furnace consists of the simultaneous melting of stainless scrap and scrap with a relatively low chromium content. After melting is complete the carbon percentage is higher than desired. Iron ore is, therefore, added to the slag to reduce the carbon. This requires a temperature of about 1820°C. (3300°F.). The heat is then worked in the usual manner by deoxidizing the slag to reduce the oxides.

25. Melting Chromium-steel Scrap in the Open-hearth Furnace.—Experiments have been made recently on melting low-carbon high-chromium heats from scrap in a small specially designed open-hearth furnace of the Bosshardt type, which uses built-in gas producers. Tour and Lippert(445) described a typical heat made in such a 3.5-ton furnace. The charge consisted of crop ends and a small amount of low-carbon ferrochromium. The metal melted quietly. A slag consisting of equal parts of fluorspar, ferrosilicon containing 75 per cent silicon, and a calcium-silicon alloy containing 30 per cent calcium was used. Only 150 lb. of slag was necessary for a 6000-lb. heat. Manganese, to deoxidize, was added as the low-carbon 80 per cent manganese alloy. The furnace was operated like a crucible, and no refining was done. It is claimed that steel of high quality can be produced using light scrap such as clippings, punchings, and similar material. Tour* commented on this as follows:

> Experiments have also been made on melting low-carbon high-chromium heats from scrap in an open-hearth furnace fired with oil or

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* S. Tour, private communication.

gas through ports in the roof. No details of the melting procedure are available, but steels produced are said to have met all requirements as to cleanliness, corrosion resistance, physical properties and workability prescribed in U. S. Federal Specifications. Since early 1937, low-carbon high-chromium heats are being produced commercially in natural-gas fired open-hearth furnaces of 4- and 6-ton capacity. These furnaces have taken the place of the Bosshardt furnace previously described and the same quality steel is being produced. However, the slag procedure is not the same.

From the foregoing it is evident that there are a number of methods of remelting stainless-steel scrap, and the very number indicates the difficulties involved in the problem. It is likely that in the future still further methods will be developed, some of which may be simpler than the ones now in use. In the last analysis the practicability of remelting stainless-steel scrap is primarily an economic problem.

D. POURING PRACTICE

The whole series of stainless irons and steels comes under the mill classification of high-quality, small-tonnage products and is, therefore, always teemed into big-end-up ingots using hot tops to reduce pipe in the ingot proper and thus to lessen the amount of scrap discard. According to Houdremont,(143) ingots may be either top- or bottom-poured, and experience has shown that neither method has a decided advantage over the other. Owing to the high solidification temperature of most of the high-chromium alloys and their drastic corroding action on refractories—especially severe in the case of the 18-8 material—particles of runners and spout may, in bottom pouring, be carried into the ingot. On the other hand, Houdremont believes that bottom-poured ingots have a cleaner surface than top-poured material. This advantage is, of course, evident in bottom-poured ingots of practically all alloy steels. It is obviously important that ingot surfaces be as clean as possible. Much of the expense of the later cleaning of bars and billets would be eliminated if the original surface of the ingot were kept free from scabs and splatters and other defects.

26. Precautions in Pouring.—The following is taken from Farnsworth and Johnson's(492) paper:

Normal alloy and stainless heats are handled in much the same manner with respect to tapping and pouring. All precautions are taken to prevent contamination of the metal. A runner brick walled in to the spout opening of the furnace provides a tap-hole, through which the metal flows from the furnace into the ladle. The furnace is tilted at such a rate as to keep the slag level above the tap-hole, thus holding back the slag until the tap is complete.

The ladles used are of the bottom-pour type, with mechanism on the side for operating the stopper rod. Particular consideration is given to the selection of the brick used in the ladle lining from a standpoint of softening and spalling at high temperatures. The same consideration is given to the stopper-rod sleeves, stopper heads and nozzles. These are replaced after each heat. The ladles are thoroughly cleaned and preheated as hot as possible before using. The nozzle size varies, depending on the type of steel and size of ingots cast. In pouring, the necessary care is exercised to pour at the proper rate to avoid splash and ensure a good ingot surface. Normal alloy and stainless heats are cast into molds of various sizes and design. Ordinarily, ingot molds designed to avoid flute or corner cracks in normal alloy steel will be satisfactory for stainless steel. The more complicated types, for example 25 per cent chromium and 20 per cent nickel, are better handled in molds of smaller cross-section. The size of ingot in most cases is governed by the size of the finished product. In preparing the molds for normal alloy heats, a tar coating is applied to the inside surface. For stainless heats, a coating consisting of aluminum powder, shellac and alcohol is used instead of tar, in order to avoid any possible carbon pick-up. Best results are obtained with a mold temperature of slightly above 65°C. (150°F.) when applying tar. A lower temperature is more desirable when applying the aluminum coating.

27. Pouring Practice for the Austenitic High-chromium Steels.—The various grades of high-chromium steels, usually classed as austenitic, martensitic, semiferritic, and ferritic, differ markedly in the care that must be exercised in the teeming of the ingots and in handling the ingots before they are reheated for forging or rolling. The low-carbon 18 per cent chromium, 8 per cent nickel and other high-chromium, high-nickel steels which freeze in the austenitic state and which normally remain austenitic in cooling to room temperature are the easiest to handle. According to Smith,(245) there seems to be no limit to the ingot size; 30-ton ingots have been made.

Austenitic chromium-nickel steels—and, according to Houdremont,(143) all other austenitic steels as well—freeze with very large columnar crystals that grow perpendicular to the wall of the mold, producing in the square mold with rounded corners the familiar X-shaped pattern illustrated by Smith(245) and others.(373) This drastic transcrystallization may be the result of a wide temperature range for freezing and of low thermal conductivity.(143) No phase change takes place in austenitic steels, and the ingots may be stripped while still hot and immediately reheated for rolling or forging. It is not possible to refine the grain of these materials by annealing although, as is well known, heating to a high temperature will effect the solution of certain precipitated carbides. The austenitic chromium-nickel steels, owing to the large columnar crystals, are tender, and the ingots must be handled carefully in reheating and in the initial breakdown in rolling. This is discussed in Chapter III.

Speransky(406) recommended pouring austenitic ingots through a tun-dish with a hole large enough so that a 1000-lb. ingot will be filled in 45 sec., an additional 25 to 30 sec. being allowed to fill the hot top.

28. Pouring Practice for Martensitic and Ferritic High-chromium Steels.—The martensitic high-chromium steels include those with about 14 per cent chromium and 0.20 per cent or more carbon. According to Parmiter,(390) the cutlery grades are among the most difficult of all alloy steels to produce satisfactorily.

> Experience has shown them to be most susceptible to surface seams, internal segregates, and non-metallic inclusions of any steel known to modern tool-steel metallurgy.

In general, the characteristics of cutlery-steel ingots are the same as of other high-alloy air-hardening steels. If the ingots are poured too hot and too fast, or if they are cooled too rapidly after pouring, surface cracks tend to develop. The transcrystalline zone in these steels depends, according to Houdremont,(143) on the pouring temperature and pouring rate, but it is always present to some extent. Because there is a transformation (A_3) in these steels, it is possible to control their grain size by annealing. Martensitic chromium-steel ingots are cooled as slowly as possible. Speransky(406) recommended cooling in the mold for 12 to 16 hr. before stripping or stripping 1 hr. after teeming and annealing for 24 hr.

The ferritic low-carbon 16 to 30 per cent chromium steels and semiferritic steels (0.12 per cent carbon and 12 to 15 per cent chromium) show a very slight tendency toward transcrystallization amounting to only a few tenths or even hundredths of an inch,(143) which is about one-third to one-fourth of the depth of the zone of columnar crystals in the martensitic types. The semiferritic steels are usually fine grained. The ferritic steels, on the contrary, are coarse grained, but nitrogen additions will reduce their grain size.

E. AUTHORS' SUMMARY

1. The melting of high-chromium steels involves special problems because chromium readily combines with both oxygen and carbon. This makes it necessary to melt and refine in such a manner that in the final stages both oxidizing and carburizing conditions are avoided so far as possible. The lower the required carbon content of the steel, the more difficult is the problem. Although a number of special processes have been developed to introduce chromium into the melt in some form other than low-carbon ferrochromium, the standard process of melting, responsible for the largest tonnage of stainless steel produced today, is the one by which chromium is introduced as low-carbon ferrochromium.

2. In the standard process of melting stainless steels without the use of stainless-steel scrap a steel bath is prepared with or without nickel, and the carbon in this bath is oxidized to a suitably low value, generally as low as possible. The slag is then removed, and the bath is deoxidized with small amounts of manganese and ferrosilicon or ferrosilicon-zirconium. A new lime-silica slag is prepared, and low-carbon ferrochromium is added through this slag, the oxidizing power of this slag being kept to a minimum by fine ferrosilicon or equivalent additions. After final manganese and silicon additions, or special additions such as calcium-silicon, the steel is tapped.

3. Up to 40 per cent stainless-steel scrap may be used successfully in the preparation of a bath of stainless steel. Scrap may be added with the steel charge or immediately thereafter. Following the scrap addition, the chromium in the slag is reduced by means of ferrosilicon or other deoxidizer, after which ferrochromium is added in the usual manner. The arc furnace or the induction furnace is used for this operation.

4. When larger quantities than 40 per cent stainless-steel scrap are to be melted, the arc or the induction furnace is employed. The use of the latter eliminates the carbon problem to a large degree. After melting the scrap, chromium in the slag is reduced with ferrosilicon, and the analysis is adjusted by means of final ferrochromium additions. Specially designed small open-hearth furnaces have been used for scrap remelting.

5. Relatively small tonnages of stainless steel are produced by the various direct processes. In general, these are based on the addition of chromium ore and ferrosilicon to the slag, the chromium as well as the iron oxide in the ore being reduced by the silicon. Such large slag volumes result that in practice as much stainless-steel scrap as available is used. This reduces the amount of chromium added as chrome ore and also the total slag volume. In one process high-carbon ferrochromium is used as a substitute or in addition to the stainless-steel scrap. In both cases, much of the chromium is oxidized with the carbon in the decarburizing period, and the chromium is then reduced from the slag by means of ferrosilicon.

6. Nitrogen in the form of high-nitrogen ferrochromium may be introduced into stainless steel during melting. The best practice involves the addition of this material after the rest of the chromium is already in the bath.

7. Big-end-up ingots with hot tops are always used for stainless steel. Either top or bottom pouring may be used, although the former predominates. In making plain chromium steel, ingots are generally small, particularly for cutlery grades, but there seems to be no limit to ingot size in casting the austenitic steels.

8. Stainless steels are more susceptible than ordinary steels to a condition commonly known as "gassy ingots." This gassiness is apparently not due to the carbon-oxygen reaction. It may be avoided by using dry raw materials and by limiting carefully the silicon content of the bath until the very end of the heat.

9. Although the chemical reactions from the standpoint both of equilibrium conditions and of reaction rates are well understood, the application of this knowledge is more an art than a science. Thus stainless-steel melting requires unusual skill and specialized technique. It can only be learned by doing, and the very best description will not suffice for the uninitiated.

CHAPTER III

FABRICATION OF 12 TO 30 PER CENT CHROMIUM STEELS

Effect of Composition on Hot Working the Ingots—Manufacture of Bars, Rods, and Tubes—Manufacture of Wire and Other Cold-worked Products—Manufacture of Plate, Sheet, and Strip—Authors' Summary

The procedures employed in hot working ingots of high-chromium steels vary considerably, depending upon their chromium and carbon contents. Undoubtedly, the carbon in the steels has a greater influence on hot workability than the chromium. With 12 to about 16 per cent chromium, even the low-carbon steels are air hardenable, and an increase in carbon content beyond 0.10 per cent intensifies the air-hardening characteristics; it also makes the steels harder at the initial hot-working temperatures, and this, together with an increase in hardness at lower temperatures during hot working, determines the procedure for breaking down ingot structures With chromium contents of 16 to 30 per cent, low-carbon steels do not harden; but there is an increase in grain size which greatly influences hot workability. As in the lower chromium steels, increasing carbon renders hot working more difficult.

A. EFFECT OF COMPOSITION ON HOT WORKING THE INGOTS

The first consideration in forging or rolling these steels is the size of the ingot. The chromium and carbon contents have an important bearing on the possible cross-sectional dimensions of the ingots to be cast. For the purpose of discussion, the high-chromium materials have been divided into five groups; *viz.*, those containing (*a*) 12 to 14 per cent chromium and 0.30 to 0.40 per cent carbon (cutlery steels); (*b*) 16 to 18 per cent chromium and 0.60 to 1 per cent carbon (cutlery steels); (*c*) 12 to 14 per cent chromium and 1 to 2 per cent carbon (die steels); (*d*) 12 to 14 or 16 to 18 per cent chromium and 0.12 per cent maximum carbon (corrosion-resistant alloys); and (*e*) 20 to 30 per cent chromium and 0.25 per cent maximum carbon (heat-resisting alloys). According to Smith,(245) the high-carbon steels (groups *a*, *b*, and *c*) are cast preferably into ingots less than 10 in. across the section, while the lower carbon corrosion-resistant alloys may be cast into ingots weighing up to 10 tons. Monypenny,* however, stated that 14-in. square ingots of the cutlery-steel type are cast regularly in England, and that, for engineering purposes, these steels have been cast into ingots of at least 5 tons in weight. The heat-resisting 25 per cent chromium alloys are cast into large ingots. The resulting extremely large grain formerly caused difficulty in hot working; proper soaking, however, has proved effective in overcoming some of the trouble, and the remainder has been remedied largely by adding 0.15 to 0.20 per cent nitrogen to the steel.

In some instances, other metals such as molybdenum, tungsten, nickel, or vanadium are added in varying amounts to modify the properties of high-chromium alloys. As such additions cause no great change in hot-working characteristics, these more complex materials are also covered by the subsequent discussion.

Owing to the formation of large dendritic crystals on solidification, the fabrication of high-chromium steels from the ingot presents more than the usual problem, and the shape of the ingot is of relatively great importance. According to Smith,(245) a great many different molds have been designed with the idea of protecting the surfaces and overcoming rolling difficulties. Both objectives are largely accomplished in an ingot with concave faces so shaped that the shrinkage causes the corners to pull away from the mold; thus, ingots with flutes designed to avoid cracks are useful. For flat-rolled products, slab-shaped ingots are successfully employed. No single shape or size will meet all the requirements, and in practice the shape and size of the ingot are determined by the final size and composition of the product.

29. Heating High-carbon Cutlery and Die Steels. Steels of the cutlery and die types are subject to air hardening, and the manner of heating the ingots to the initial hot-working temperature is of first importance. The practice outlined by Parmiter(121) consists of stripping the ingots while hot, preheating them in a gas-fired semimuffle furnace at 760 to 815°C. (1400 to 1500°F.), and then heating to the initial hot-working temperature, 925 to

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* Private communication.

1095°C. (1700 to 2000°F.). The ingots are soaked at the preheating temperatures and gradually brought to the working temperatures with minimum time for uniform heating. In general, the heating periods are longer than for carbon steels owing to low heat conductivity. If for any reason the ingot must be cooled to room temperature, the cooling rate must be low to prevent cracking or checking because of air hardening Annealing at 845 to 900°C. (1550 to 1650°F.) or tempering at 700°C. (1290°F.) is usual to permit grinding or chipping the surface for the removal of defects. Such surface conditioning is necessary because edges of cracks and other defects do not even partially weld during the subsequent hot-working processes.

30. Forging and Rolling the High-carbon Steels.—These steels are seldom, if ever, rolled directly from the ingot. The ingots are generally hammer forged to billets, and, according to the observations of Parmiter,(121) Zieler,(251) Thompson,(298) and Fiske,(314) this demands great care. Heating usually requires at least 1 hr. per in. of thickness to attain a temperature of about 1095°C. (2000°F.). Then the forging is started, using light blows to break up gradually the ingot structure near the surfaces. Zieler(251) emphasized the necessity of keeping the hot-working temperatures below 1150°C. (2100°F) to prevent burning and to eliminate cracking caused by "ledeburite" (carbide structure) in the steels. As forging proceeds, the ingot is given heavier blows to work the metal more quickly. During the forging process, the metal is reheated a number of times to avoid working at temperatures below about 780°C. (1440°F.). The customary practice is then to anneal the rough forging at 845 to 900°C. (1550 to 1650°F.), descale by pickling or sand blasting, and then remove defects by grinding or chipping. According to Snyder,(405) steels of this type are pickled with solutions containing 10 to 15 per cent sulphuric acid heated to 65 to 75°C. (150 to 165°F.), although sometimes a little hydrochloric acid is added. Further details on pickling practice are given in later chapters. In grinding, the surfaces of the metal must not be overheated or grinding cracks will result.

The cleaned billet is hammer forged, drop forged, or rolled to the finished product. In any case, the billet is brought up gradually to about 760°C. (1400°F.) with the furnace, held for preheating, and then brought to 1095°C. (2000°F) for the final hot-working operation. All this is done in the normal furnace atmosphere. Working too long at the higher temperature produces excessive grain growth, but Fiske(314) reported that, if properly heated, these steels are forged as readily as ordinary steels. Thompson,(298) however, stated that, even under the most favorable drop-forging conditions, the die life is only about 75 per cent of that for carbon steels. If the billet is to be hot rolled, the best results are obtained on hand mills. As explained by Smith(245) and Parmiter,(121) this gives an opportunity for closer control of rolling temperatures and for reheating at intermediate stages.

The finished forged or rolled product is annealed, descaled for inspection purposes by pickling or sand blasting, and machined or ground according to requirements. Hardening and tempering are customary; this requires subsequent grinding, lapping, or polishing. Plates, sheets, rods, wire, and tubing are fabricated by the methods outlined in the subsequent discussion of the lower carbon steels, with the exception that the previously specified initial and finishing temperatures apply.

31. Heating, Forging, and Rolling Low-carbon 12 to 30 Per Cent Chromium Steels.—Steels of this group comprise those corrosion- and heat-resisting types which contain from 12 to 14 or from 16 to 18 per cent chromium with a maximum of 0.12 per cent carbon and from 20 to 30 per cent chromium with a maximum of 0.25 per cent carbon. They are sometimes modified by the addition of varying percentages of nickel, molybdenum, silicon, copper, and other elements. While the 12 to 14 per cent chromium steels are subject to air hardening, those of the higher chromium contents are not. Thus, in heating for forging or rolling, the air-hardening properties of the lower chromium steels must be given due consideration, whereas with the higher chromium types the chief concern is large grains.

Generally, ingots of low-carbon high-chromium steels are broken down in a blooming mill. As the thermal conductivity of these steels is low, they are usually stripped hot and charged directly into soaking pits or furnaces with the flames off to avoid rupture. Johnson and Sergeson(230) recommended preheating near the lower limit of the range from 870 to 1095°C. (1600 to 2000°F.) to avoid excessive increase in grain size and to prevent decarburization. For example, a 20-in. round or square ingot is heated for a total of 10 to 15 hr., during which time it is thoroughly soaked at the lower temperatures, and then gradually brought to the initial hot-working temperature, about 1150°C. (2100°F.). Care is necessary to avoid decarburization, which occurs if the ingots are held too long at the initial rolling temperature. Decarburization is accompanied by large grains, which increase the tendency to tear during subsequent hot working.

The initial breaking down of the ingots by blooming is of utmost importance because of its serious effect on the mill yield. Johnson and Sergeson(230) reported that the properly heated ingots for the blooming-mill operation should be given light initial drafts in the beginning to avoid rupturing corners or tearing the surface of the steel, and that the success of this operation depends upon the experience and skill of the operator; if cracking starts, he must discontinue rolling and reheat.

If forging is employed for the initial breakdown, the heating periods should be slightly longer and the forging temperatures about 30°C. (50°F.) lower than those required for rolling. The experience of Johnson and Sergeson indicates that forging hammers are more appropriate than forging presses, because the time of contact between the hot metal and the cold anvil and pallet is much shorter and the hammering action refines the grains near the surface of the ingot to a greater degree. In forging after the first heating, dimensions are reduced as little as 0.5 in. on a side, but after the ingots have been reduced to 75 per cent of their original cross-section, reductions as great as 1 in. on a side may be made without reheating and without danger of cracking. During forging, the edges of the ingot must be flattened at regular intervals to eliminate corner checking, and, as in rolling, the final forging temperatures should not be much less than 870°C. (1600°F.).

B. MANUFACTURE OF BARS, RODS, AND TUBES

The products from the blooming-mill and forging operations vary greatly in cross-sectional dimensions depending upon the anticipated shape of finished product. As stated by Smith,(245) stainless-steel rounds, bars, and rods are the product of one type of mill, and stainless-steel plates, sheets, and strips of another. The surface condition of the finished product is of great importance as any defects not removed from the slabs and billets are carried through to the finished products. As recommended by Snyder,(405) the intermediate products must be sand blasted or pickled, ground, chipped, machined, or otherwise surface conditioned before further rolling. Slabs or billets of the 12 to 14 per cent chromium material are annealed at 845°C. (1550°F.) or tempered at 705°C. (1300°F.) before the surface conditioning.

32. Rolling Bars and Rods.—Bars larger than about 3 in. in diameter are fabricated on the blooming mill or forged directly from the ingot, but smaller bars and rods are rolled from billets. According to Johnson and Sergeson,(230) the slow-speed hand mills used for tool steels yield the best results. It is impracticable to roll bars and rods of high-chromium steels on mills designed for carbon or low-alloy steels since the chromium steels tend to spread the rolls and require tighter guides. The most important bar sizes are produced by the "hand-round" method and the smaller rods, down to ¼ in., by well-handled guide mills, the rods being made from billets as small as is practicable.

The hot-rolled bars and rods are then annealed. Pierce and Grossmann,(393) and many others before and since, stated that the 12 to 14 per cent chromium steels are annealed by holding at 705 to 760°C. (1300 to 1400°F.) for several hours (depending on the thickness) and air cooling. This material is hardened by heating to 955°C. (1750°F.) and oil quenching, followed by tempering between 315 and 540°C. (600 and 1000°F.) or between 600 and 700°C. (1110 and 1290°F.). Monypenny(191) emphasized that tempering between 550 and 600°C. (1020 and 1110°F.) has a bad effect on corrosion resistance. Avoiding this temperature range is almost the only limitation in the heat treatment of these steels, which, like carbon steels, offer a wide choice of properties. The 16 to 18 per cent chromium steels are softened by air cooling after holding at 760 to 790°C. (1400 to 1450°F.); the 25 per cent chromium steels are cooled quickly from 900°C. (1650°F.) for the same purpose. After softening, the steels are descaled; Snyder(405) suggested a solution of 10 per cent hydrochloric and 0.5 per cent hydrofluoric acids heated to 55 to 65°C. (130 to 150°F.); but sulphuric acid and sodium chloride, as well as many other pickling solutions, are common. The bars are cut to size and may be ground or machined if necessary, while the smaller (¼-in. diameter) rods may be cold drawn to wire.

33. Rolling of Seamless Tubes.—Seamless tubes are made industrially of either low- or high-carbon high-chromium steels. Most tubes are made from the lower carbon variety. Dependent upon size, the tubes are rolled from blooming-mill rounds or bar-mill rounds. Details concerning the practice to be employed have not been published, but Newell(384) stated that the manufacturing processes used are essentially the same as those for carbon and low-alloy steels. Exactness of mill setup, and central location and type of surface of the piercer point, are important to prevent marking of the inside of the tube. A smooth central rod is frequently used as a mandrel.(254) Piercer points and rolling-mill plugs of special composition are employed to produce long tubes of high quality, and the temperatures for piercing and rolling are controlled accurately. According to Newell, the 16 to 18 and the 25 to 30 per cent chromium steels, being relatively soft when hot, are easily marked by guides or rolls; overheating causes grain growth and results in poor or ruptured surfaces. He further stated that piercing these steels does not require more power than piercing carbon steels, whereas piercing those with 12 to 15 per cent chromium, even with low carbon, does require more power. Steels of the following analysis are commonly used in the manufacture of seamless tubes(384):

Element	Percentage		
	Type 1	Type 2	Type 3
Carbon	0.12	0.12	0.15
Manganese	0.50	0.50	0.75
Silicon	0.50	1.25	0.60
Sulphur	0.03	0.03	0.03
Phosphorus	0.03	0.03	0.03
Chromium	12 to 14	16.5 to 18.5	26 to 30

With few exceptions, the seamless tubes of these compositions are used in the fully annealed state. In rare cases, tubes of the 12 to 14 per cent chromium type, some with higher carbon, are hardened and tempered. The range of properties regularly obtained is shown in Table 4, page 59. The exact properties naturally depend upon the diameter and wall thickness of the tube, and upon whether the test was made on a full-sized tube or a strip cut from it. But "cold-drawn or small-diameter tubes are usually softer and more ductile than hot-finished tubes, even with equivalent annealing practice."

Tubes made of the various steels are successfully cold drawn in dies of the shape used for plain carbon steels. Lubrication is the chief problem. The most suitable lubricant, metallic lead, is applied to the surfaces of the tube by dipping in a lead bath covered with a suitable flux. The tube may be heated to 200°C. (390°F.) or, as in the Dudzeele process, may be cold when introduced into the lead bath. After leading, the tubes are cold drawn; 15 per cent reduction per pass is usual for the 18 per cent chromium steels. After a number of passes it is necessary to remove the lead coating, anneal and pickle, and then relead the tube for continued cold drawing to the finished size.

C. MANUFACTURE OF WIRE AND OTHER COLD-WORKED PRODUCTS

The usual manufacturing procedure for high-chromium steel wire begins with ¼-in. diameter rods in coils weighing up to 50 lb. or more. While most wire is made from steels of the 18 per cent chromium, 8 per cent nickel type, there is a small but consistent production of wire of the plain chromium steels in the fine sizes. Wills and Findley(413) reported that, as with most steels, the first step consists of annealing the ¼-in. diameter rods and then descaling with a hot 10 per cent sulphuric acid solution. This is followed by the usual washing, liming, and drying. In some instances, the rod is lead coated for the initial drawing operations. The low-carbon 25 per cent chromium steels are almost invariably so coated. For other analyses, such as the 12 to 14 and 16 to 18 per cent chromium steels, limed wire is used with dry soap as a lubricant.

34. Precautions in Wire Drawing.—Special importance is attached to the speed of drawing and to the type of die material. Wills and Findley(413) stated that best results are obtained by drawing at relatively low speeds (as compared with those used for carbon steels) and by drawing through a high-carbon chromium die steel. These die steels are used on the sizes extending from about 0.25 to 0.10 in. in diameter. According to the same authority, tungsten carbide dies with no lubricant other than dry soap should be used for drawing below 0.10 in. In drawing plain chromium steel wire to a given size, the extent of reduction before annealing varies so much according to the particular conditions that it is inadvisable to cite a definite procedure. However, certain precautions are always observed in producing a wire of good quality. The rods must be annealed and free of defects, such as slivers and seams, and must be thoroughly cleaned of scale. Pickling both before and after annealing is common as is the use of mechanical scale breakers or brushes and agitation in the pickling bath. Any scale is likely to be forced into the surface of the wire and would later result in excessive corrosion. The wires of small diameter should be annealed in a furnace with a non-scaling atmosphere maintained by the introduction of hydrogen or nitrogen. This may eliminate the final pickling. Wills and Findley stated that low-carbon 16 to 18 per cent chromium steel wire is used for screens, woven belts, and stitching wire, as well as for cold-forming or heading operations.

35. Making of Screws, Bolts, and Nuts.—Fasteners such as small screws, bolts, and nuts having a diameter of less than ⅜ in. are made from annealed wire. Like similar parts of ordinary steels, they are manufactured by threading, cold heading, and cold punching, and it is important that the wire be free from seams and other surface defects. Peterka(391) described the fabrication of these products from wire of the low-carbon 12 to 14, 16 to 18, and 20 to 30 per cent chromium steels. The higher carbon steels cannot be deformed sufficiently when cold. The wire is provided with a lubricating coating which consists of a mixture of lime or soap and tallow; sometimes it is coated with a metal such as copper. According to Peterka,(391) the annealed high-chromium steels of this type require approximately 30 to 40 per cent more power for cold working than annealed low-carbon steels and are headed only 40 to 70 per cent as readily as common steel for screws and bolts. This difference is reflected in tool life and in the filling of head shapes and sharp corners. He explained that it is good economy to use dies and hammers made from the best types of carefully heat-treated die steels. After cold heading and cold punching, products made from 12 to 14 per cent chromium steels need no heat treatment if the diameter is less than ⅛ in. and simple upsetting operations are involved. If the diameter is greater than ⅛ in., the part should be heat treated. Heat treatment is not required for simple upset parts of the 16 to 18 per cent chromium steels when the diameter is less than 3/16 in., but larger sections should be heat treated. Air cooling from 955°C. (1750°F.) followed by tempering at 700°C. (1290°F.) is recommended for the 12 to 14 per cent chromium steels. The 16 to 18 per cent chromium steels should be air cooled from 705 to 730°C. (1300 to 1350°F.), and the 20 to 30 per cent chromium steels should be cooled rapidly from 900°C. (1650°F.). The scale formed on the steels is removed by pickling with a solution of 10 per cent sulphuric acid and 10 per cent rock salt heated to 80°C. (180°F.), followed by washing and dipping in 30 per cent nitric acid solution.

Slotting of screws can be done at the usual rates with high-speed saws having fine teeth and ample rake. During the operation the saw must cut into, rather than ride on, the surface. Peterka recommended that, for screws requiring only a simple upsetting operation, the free-machining type of steel be used. The only important difference in threading stainless and ordinary steel is that the cutter used on stainless steel has a four- to five-thread lead instead of the usual two- to three-thread lead.

Immediately after forming (or after annealing and pickling following the forming), fasteners of this type are tumbled in a barrel containing soapy water and are given no further polish unless specified. Bolts, nuts, and screws are passivated with nitric acid either before or after the tumbling. Passivation is important to take care of small particles of tool steel which may become attached to the surface in the course of manufacture. Such particles are removed when the parts are immersed for about 20 min. in a 10 to 20 per cent nitric acid solution heated to 60°C. (140°F.). The finished parts are then placed in cadmium-plated boxes to prevent them from coming into contact with rust. To determine whether they have been properly cleaned and passivated, or to remove common steel products which may be present, the fasteners are immersed in a copper sulphate solution for about 2 min. Particles or parts of ordinary steel will be coated with a copper deposit and can readily be rejected.

Bolts and nuts larger than ½ in. in diameter are fabricated by drop forging. The initial forging temperature is about 1095°C. (2000°F.), and the finishing temperature should be above 900°C. (1650°F.), except for the 16 to 18 per cent chromium steel, which is finished at 760°C. (1400°F.) to obtain fine grain. Thompson(298) stated that to avoid overstressing in upsetting and heading, as many passes as practicable are required. The bolts and nuts are finally annealed and pickled according to the procedure usual for chromium steels.

D. MANUFACTURE OF PLATE, SHEET, AND STRIP

According to Curtiss,(354) stainless-steel plate as distinct from sheet begins at a thickness of 3/16 in.; this thin plate is rolled up to 200 in. long and up to 90 in. wide. Plate of 5/8-in. thickness may be as long as 300 in. and as wide as 160 in. The dimensions are determined by the size of the available rolling mills and are limited by the amount of sound metal which the steel maker can furnish in one ingot. Curtiss pointed out that rolling large plates is very different from making other high-chromium steel products as, in general, the plate must be finish-rolled from the slab in one heating. Occasionally it is necessary to reheat once, but, owing to the difficulties of handling, anything but a single conversion from slab to plate is not considered commercial practice. The slab from which the plate is to be made should be cleaned and freed from slivers and cracks, and its size should depend on the final plate dimensions. Curtiss warned against the following: (*a*) direct rolling of the ingot to the plate; (*b*) a slab that is extremely long and severely tapered; (*c*) a slab with deep chipping or grinding on the longitudinal edges; and (*e*) a slab with concave longitudinal edges. In an ideal slab the length is 1.5 to 2 times the width; the ratio of slab thickness to gage of finished plate is between 15 to 1 and 20 to 1, and the longitudinal edge is square or slightly convex.

36. Plate Rolling.—Slabs for plate rolling are preheated by soaking in a furnace heated to about 870°C. (1600°F.), after which the furnace and the steel are brought to initial rolling temperature, about 1150°C. (2100°F.). Preheating is necessary to avoid internal cracks or surface checking of the slab. The plate is first rolled with dry rolls to assist in maintaining plate temperature because reductions per pass are smaller than normally used for carbon steel and at the same time all the work must be done without reheating. The amount of dry rolling is dependent upon the relative size of the mill slab and the final plate. Generally, a plate of light gage and large area requires more dry rolling than one of heavier gage and smaller area. Thus, in production rolling of these steels there is real danger of overheating the rolls. The better practice involves alternate rolling of carbon- and stainless-steel plates to keep the rolls cool enough.

The best type of mill for rolling high-chromium plate is a two- or four-high reversing mill. In the first pass or two, scale is removed by application of salt or water-soaked bags. Cross rolling for width is the next step. Since these steels are more resistant to plastic deformation than carbon steel, the tendency to overroll the top and bottom is more pronounced. This produces laminations and folds so that a larger allowance is made for side scrap. Following cross rolling, the slab is rolled longitudinally to the proper gage. The drafts per pass should be approximately 60 per cent of those used in rolling ordinary carbon steels. Curtiss stressed the need for speed and for absence of interruptions in rolling stainless-steel plates to maintain the highest finishing temperature possible. This is particularly true in making wide material of a light gage, such as plates of 3/16- and ¼-in. gage, which tends to cool rapidly to a temperature too low for satisfactory rolling.

After rolling, the plates are too hard to flatten in straightening rolls. This operation and shearing of the plate to size are usually deferred until after annealing. The low-carbon steels containing 12 to 18 per cent chromium are annealed at temperatures from 760 to 790°C. (1400 to 1450°F.) and air cooled, whereas the 20 to 30 per cent chromium steels are annealed at about 900°C. (1650°F.) for a number of hours and cooled rapidly. The plates are then sand blasted or pickled, passivated, and sheared to the proper size. Sand blasting particularly should be followed by a thorough passivating treatment in nitric acid.

37. Hot- and Cold-rolled Sheet and Strip.—Conditioned slabs are the most suitable material with which to start fabrication of sheet and strip. Johnson and Sergeson(230) noted that typical dimensions of a slab for sheet manufacture are approximately 2.5 by 14 by 30 in. The low-carbon 12 to 14 and 16 to 18 per cent chromium steel slabs are first heated to temperatures between 815 and 870°C. (1500 and 1600°F.), and the 25 per cent chromium steel slabs to between 815 and 980°C. (1500 and 1800°F.). The heated slabs are usually broken down to about ¼ in. on a jobbing mill, using from 15 to 25 per cent reduction per pass. While hot, they are flattened and sheared into sheet bars of the required width and length. These are then rolled on the standard mills with a net production rate of about one-third of that usual for ordinary steel sheets. Frequent reheating and reductions of about 15 per cent in each pass (as compared to 25 per cent for rolling soft steel) account for the difference. The finishing temperature for low-carbon 12 to 14 and 16 to 18 per cent chromium steels should be about 650°C. (1200°F.) to produce steel with relatively fine grain. The finishing temperature for the 25 per cent chromium steels should be between 650 and 815°C. (1200 and 1500°F.).

The sheets are then descaled and, if a hot-rolled product is desired, sheared to size. The usual annealing treatment for the low-carbon 12 to 14 and 16 to 18 per cent chromium steels consists of heating at 760 to 800°C. (1400 to 1475°F.) for a short period, followed by air cooling. This operation may be carried out in a continuous annealing furnace. Johnson and Sergeson stated that if the carbon content of the steels is above 0.12 per cent, they should be box annealed at 845 to 870°C. (1550 to 1600°F.) and cooled slowly. Sheets of 25 per cent chromium steel are heated to about 900°C. (1650°F.) and cooled rapidly. Removal of the scale by a solution containing 10 to 15 per cent sulphuric acid and 5 to 25 per cent hydrochloric acid heated to 75°C. (165°F.) is advocated by Snyder.(405) If difficulty is encountered in removing the scale, the sheets are scrubbed and treated with a 10 per cent nitric acid solution containing about 2 per cent hydrofluoric acid heated to 55°C. (130°F.). It is essential to finish the sheet with a dip in 20 per cent nitric acid heated to 55°C. (130°F.) to passivate the steel.

Cold rolling produces a better surface. This is ordinarily carried out on a four-high cluster mill or its equivalent. About 10 per cent reduction in one or more passes is usual, after which the sheet is annealed, pickled, and cold rolled further. The sheet is finally flattened on a roller leveler or a stretcher leveler and is rigidly inspected for surface and gage.

Strip also starts from conditioned slabs. The slabs ordinarily employed, according to Johnson and Sergeson, are about 3 in. thick, 8 to 15 in. wide, and long enough to make about 100 ft. of finished strip. Higher initial rolling temperatures (than in sheet rolling), about 1095°C. (2000°F.), are used for the 12 to 14 and 16 to 18 per cent chromium steels, and 1150°C. (2100°F.) is necessary for the 25 per cent chromium steels. The slabs are generally heated in continuous pusher-type furnaces and are covered with scrap sheet to prevent excessive oxidation. Hot rolling is done on 24-in. reversible two-high universal mills, and the strip is coiled.

The coils are then annealed, the annealing temperatures for the 12 to 14 per cent chromium steels again being in the vicinity of 760 to 815°C. (1400 to 1500°F.). Continuous annealing may be used if the carbon content is 0.10 per cent or lower, but with carbon above 0.12 per cent the steels are box annealed for best results. Such steels are frequently used for cutlery. After normalizing, their hardness is about 40 to 45 Rockwell *C*; this may be further increased by cold rolling. The steels containing 16 to 18 per cent chromium are continuously annealed at about 845°C. (1550°F.), and the 25 per cent chromium steels are similarly annealed at about 900°C. (1650°F.). Coils are pickled in the same way as sheets.

Large quantities of the 16 to 18 per cent chromium steel are produced as cold-rolled strip. The cold rolling is done on tandem stands of massive four-high mills and is followed by continuous annealing at 815 to 845°C. (1500 to 1550°F.) and pickling with a 10 per cent hydrochloric acid solution, containing 0.50 per cent hydrofluoric acid, heated to 55 to 65°C. (130 to 150°F.). In cold rolling, slippage must be avoided as it ruins the surface. Johnson and Sergeson also stated that cold-rolled strip of the 25 to 30 per cent chromium steel can be produced only with difficulty as the free carbides in the steel cause the working rolls to become badly marked when the thickness of strip gets below 0.035 in.

38. Polishing and Buffing.—Polished sheet and strip of plain high-chromium steels are produced in large quantities, mainly from the 12 to 14 and 16 to 18 per cent chromium grades. In preparing polished material it is usual, although not essential, to start with cold-rolled surfaces as these do not require the removal of so much metal as hot-rolled, annealed, and pickled surfaces. Smith(245) and Snyder(405) described progress in polishing methods. According to Smith, the polisher consists of a fabric roll 18 in. in diameter and 72 in. across the face, sized with glue and treated with abrasive grit. The grades of grit commonly used range from 60 to 80 mesh for initial polishing, and 120-mesh grit is used for further polishing. When producing mirror finish and other really fine surfaces, much finer abrasive is used for the final stages.

The roll is made of fabric disks pasted together and held on the shaft under end pressure by heavy washers and screws. The prepared roll is trimmed to obtain even cutting in polishing. The finished roll is then mounted so as to revolve on an oscillating machine. The part to be polished is placed on a reversing table below the grinding roll and passes between the grinding roll and the supporting roll. It is then transferred to a similar machine using a roll treated with finer grit. Several such rolls may be used before the final finishing operation which is performed on a reversing table over which runs a canvas belt. The belt is impregnated with abrasive of the proper size held by glue, and the operator applies pressure locally as in a sanding operation. This gives an even texture to the polished surface. The sheet is then cleaned and sheared to size.

Snyder(405) stated that the direction of polishing is changed from one roll to the next as this eliminates the polishing lines from the previous wheel. He advised against using polishing rolls that have been employed on common steel as there is danger of contaminating the surface of the high-chromium steel. The standard finishes adopted by the steel industry for sheet and strip are: hot rolled, annealed, and pickled; full finish, bright cold rolled; full finish, dull; standard polish, one or both sides; standard polish tampico brushed, one or both sides; high luster polish, one or both sides; and mirror finish, one or both sides.

Snyder suggested that polished surfaces be buffed at a speed of from 900 to 1200 linear ft. per min. and explained that the cost of this operation can be reduced by painstaking work in the prior polishing. In buffing, too much grease invariably gives a cloudy surface, and any deep initial scratches permanently mar the buffed surface. Snyder finally pointed out that the straight chromium steels gall and score readily in polishing due to loading of the polishing wheel, and this means increased time of polishing. Loading is counteracted by dressing the wheels at regular intervals so that they will cut instead of burnish.

E. AUTHORS' SUMMARY

1. All 12 to 30 per cent chromium steels are forged or rolled to industrial products. This generally involves relatively small ingots and precisely controlled heating and soaking conditions.

2. The high-carbon cutlery and die steels are forged or saddened prior to rolling, following the common practice for tool steel, and the rolling is generally carried out on tool-steel hand mills. These steels are used for knives, dies, and wear-resisting products, which are usually hardened, tempered, and ground to the final dimensions. Cutlery is then polished.

3. The lower carbon corrosion- and heat-resisting steels are generally bloomed directly from the ingot, and the finished products are rolled on hand mills. Seamless tubes of these analyses are produced by the practice usual for carbon steels, except for greater mill precision and more carefully controlled temperature conditions. In addition to seamless tubes, these steels are manufactured into bars, rods, wire, plates, sheet, strip, and fasteners. With the exception of the heat-resisting steels, all products are used as annealed and descaled; or annealed, descaled, and cold rolled; or annealed, descaled, and cold rolled and annealed.

4. Pickling or descaling is an important and special point of the manufacturing procedure. Although the general principles of analogous steps in the manufacture of carbon steels are followed, the tenacity of the scale and the relative corrosion resistance of chromium steels require special reagents and much greater care and control of these operations.

5. The products of the low-carbon corrosion-resisting steels are invariably passivated with nitric acid so that the finished material will have the greatest possible resistance to corrosion. Sheet or strip is in many instances polished and buffed to provide surfaces that vary in luster from a bright polish to a mirror-like finish. Inspection of surface is a matter that does not lend itself to technical discussion, but constant careful inspection of the chromium steels after various steps in the manufacture is essential to quality.

6. An attempt has been made in this chapter to cover broadly the manufacturing methods applied to the 12 to 30 per cent chromium steels. Further details are given in connection with discussion of particular steels, but the major steps here described are generally applicable to all plain iron-chromium alloys in this range.

CHAPTER IV

LOW-CARBON STEELS CONTAINING 10 TO 18 PER CENT CHROMIUM

Mechanical Properties—Mechanical Properties of Modified Iron-chromium Alloys—Physical Constants—Corrosion—Castings—Welding—Authors' Summary

Alloys containing a maximum of about 0.12—sometimes 0.10—per cent carbon and 10 to 18 per cent chromium are widely used in industry because of their resistance to corrosion at normal and somewhat elevated temperatures. This grade of "stainless steels" or "stainless irons" is subdivided into a group containing 10 to 14 per cent chromium and another containing 15 to 18 per cent chromium.

The 10 to 14 per cent chromium group is hardenable because sufficient austenite is formed at elevated temperatures to produce martensite upon cooling, even in air. Subsequent tempering, up to 815°C. (1500°F.), results in a wide range of hardness, strength, and toughness That useful properties can be developed is attested by the fact that an important application of the material is for steam-turbine blades. Resistance to attack by the more energetic media, however, is not so high as that of some other materials; in fact, alloys of the 10 to 14 per cent chromium group are likely to become covered with rust upon exposure to the atmosphere.

Steels of the other grade, which contain 15 to 18 per cent chromium, cannot be hardened to the same extent (hence, are often said to be non-hardenable) and are resistant to corrosion under a greater variety of, and under more severe, conditions. Their importance is apparent when it is considered that they have been used extensively in the production of nitric acid. With proper care, these steels resist atmospheric corrosion indefinitely. They have been employed for automobile trim and for similar purposes in which resistance to staining was the chief requirement.

Both grades can be hot and cold worked successfully, deep drawn and spun, as well as formed, machine welded, and riveted.

In general, they have less strength at elevated temperatures than the austenitic chromium-nickel steels, although up to certain temperatures they are equally satisfactory and are even more resistant—particularly those of the 15 to 18 per cent chromium grade—to atmospheres containing sulphur-bearing gases. Both grades have useful resistance to oxidation at elevated temperatures. The 10 to 14 per cent chromium steels are considered resistant to temperatures up to about 815°C. (1500°F.), whereas the 15 to 18 per cent chromium steels are satisfactory at temperatures up to 870°C. (1600°F.).

A. MECHANICAL PROPERTIES

Slow cooling of steels containing 10 to 14 per cent chromium, even if the carbon is relatively low, results in structural changes comparable with those obtained upon slow cooling of carbon steels. Mechanical properties after slow cooling are similar also; in the quenched and tempered condition, however, the tensile and yield strengths of these chromium steels are definitely higher than those of carbon steels of comparable carbon content. Toughness and ductility are largely dependent upon annealing temperature. Properties of greatest utility result from quenching and tempering the 10 to 14 per cent chromium steels, whereas the 15 to 18 per cent chromium steels are used chiefly in the annealed state.

39. Mechanical Properties of Annealed Steels.—In the attempt to arrive at values that may be expected of annealed steels, data of McAdam,(48) Monypenny,(101) Giles,(302) Krivobok,(499) and of several manufacturers(450,483,484) were examined. No consistent variation with chromium content is apparent in the 10 to 18 per cent range. Carbon approaching the upper limit (0.15 per cent) strengthens and hardens a given steel. The lowest tensile strength reported, 63,300 lb. per sq. in., was for an alloy containing 0.08 per cent carbon and 11.78 per cent chromium; the highest, 87,000 lb. per sq. in., was for one containing 0.12 per cent carbon and 11.97 per cent chromium. The yield-strength variation was 37,200 to 60,000 lb. per sq. in., that of elongation in 2 in. was 25 to 50 per cent, that of reduction of area was 57 to 75 per cent, and that of Brinell hardness was 137 to 170. Some of the data are summarized in Table 3.

TABLE 3.—MECHANICAL PROPERTIES OF SOME ANNEALED HIGH-CHROMIUM STEELS

Composition, per cent		Tensile strength, lb. per sq. in.	Yield strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Reference No.
C	Cr						
0.10	11.9	66,800	37,200	37	67.8	137	191
0.09	15.25	76,500	40,000	32.5	72.2	147	362
0.09	16.25	74,900	47,200	50	60.1	. .	450
0.08	17.25	79,500	53,000	34.5	. . .	179	450
0.12	18.92	72,500	43,500	32.5	63.3	149	450
0.13	20.52	82,800	53,900	25	58	163	499

Seamless tubes of low-carbon steels containing 12 to 14 or 16.5 to 18.5 per cent chromium are nearly always used in the fully annealed state. Representative property ranges for these grades, together with those for material containing low carbon and 26 to 30 per cent chromium (see page 47 for complete analysis), are given in Table 4. As mentioned in the previous chapter, the exact properties depend upon the size of the tube and the location and size of the specimen.

TABLE 4.—PROPERTY RANGES OF LOW-CARBON HIGH-CHROMIUM STEEL TUBES*

Property	12 per cent chromium steel, annealed	18 per cent chromium steel, annealed	28 per cent chromium steel, hot rolled and annealed
Tensile strength, lb. per sq. in	65,000 to 78,000	70,000 to 85,000	75,000 to 90,000
Yield strength, lb. per sq. in.	35,000 to 45,000	40,000 to 60,000	45,000 to 60,000
Elongation in 2 in., per cent	25 to 35	27 to 38	15 to 30
Brinell hardness	135 to 160	140 to 180	160 to 195
Rockwell *B* hardness	75 to 85	78 to 90	84 to 95

* Newell (381)

40. Effect of Quenching Temperature.—Specimens containing 0.08 per cent carbon and 11.10 per cent chromium were oil quenched from temperatures ranging from 870 to 980°C. (1600 to 1800°F.) by Mochel.(74) Mechanical properties are given in Table 5.

Mochel decided that a temperature of 955°C. (1750°F.) gave the best all-round results for the 10 to 14 per cent chromium steels. A somewhat higher quenching temperature 980°C. (1800°F.)—is often favored for such alloys. Both temperatures are well within the austenitic region of the phase diagram.

TABLE 5.—THE EFFECT OF QUENCHING TEMPERATURE ON THE MECHANICAL PROPERTIES OF A STEEL CONTAINING 0.08 PER CENT CARBON AND 11.10 PER CENT CHROMIUM*

Oil quenched from		Tensile strength, lb. per sq. in.	Yield strength, lb. per sq. in.	Elastic limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
°C.	°F.							
870	1600	97,800	75,600	60,000	27	70.3	207	66
900	1650	102,000	81,500	62,000	29	69.3	235	66
925	1700	106,000	91,500	69,000	21	65.2	235	63
955	1750	102,000	91,000	75,500	22.5	67	235	62
980	1800	105,000	90,000	71,500	21	68.2	235	59

* Mochel.(74)

The effect of quenching temperature on the hardness of two normalized alloys containing approximately 17 and 19 per cent chromium, as determined by Krivobok,(378) is shown in Fig. 3. These alloys are evidently somewhat hardenable by quenching from the same temperature range as that used for the lower chromium alloys; *viz.*, 900 to 1000°C. (1650 to 1830°F.). The meaning of the minimum values in the vicinity of 800°C. (1470°F.) is unknown.

These curves may be compared with those of Monypenny(191) given in Fig. 4. It is shown here that the hardening temperature increases with increased chromium content and that this effect is accompanied by decreased hardenability. Krivobok's results are in accord with these conclusions. A few other mechanical properties of materials in the "fully hard" condition are given in Table 6.

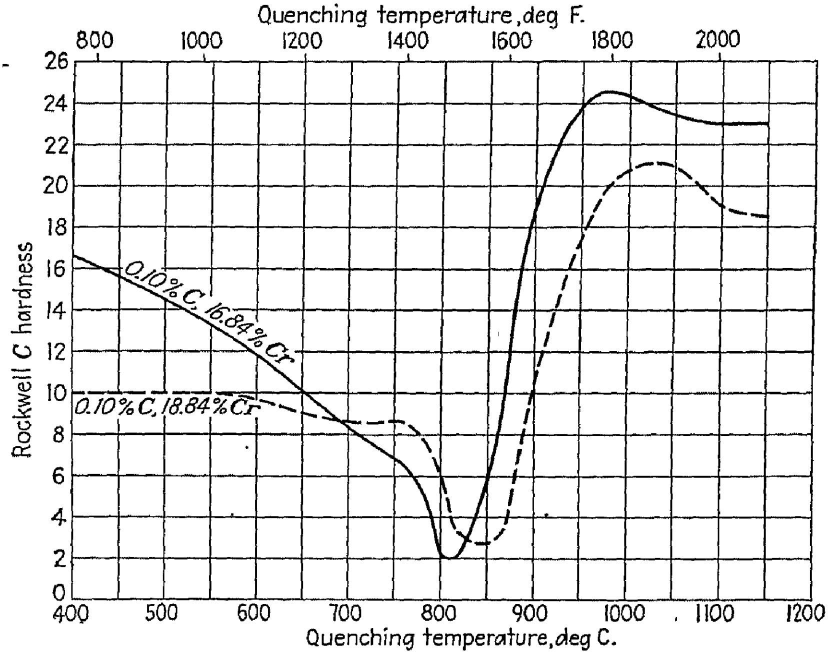

FIG. 3.—The effect of quenching temperature on the hardness of iron-chromium alloys containing 16.84 and 18.84 per cent chromium. (*Krivobok.*[378])

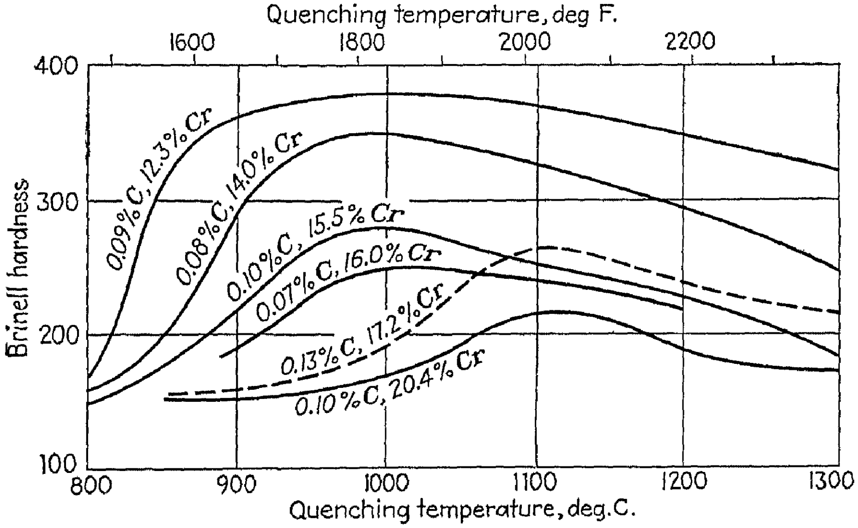

FIG. 4.—The effect of quenching temperature on the hardness of iron-chromium alloys. (*Monypenny.*[191])

TABLE 6.—PROPERTIES OF SOME IRON-CHROMIUM ALLOYS OIL QUENCHED FROM 930 TO 980°C. (1705 TO 1800°F.)

Composition, per cent		Tensile strength, lb per sq. in.	Yield strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.	Investigator
C	Cr							
0.07	11.7	164,000	149,500	13.5	42	...	28	Aitchison(24)
0.07	13.3	156,000	131,700	18.5	51	...	12	Aitchison(24)
≦0.12	12 to 16	178,000	160,500	15	51	364	...	Scharschu(391)
≦0.12	10 to 13.5	182,000	179,000	18	63	363	57*	Crucible Steel Company(450)
≦0.12†	10 to 13	200,000	134,000	10	35	418	24	Rustless Iron and Steel Corporation(806)

* Charpy impact.

† These alloys also contained ≦0.5 per cent silicon and 0.25 to 0.6 per cent manganese.

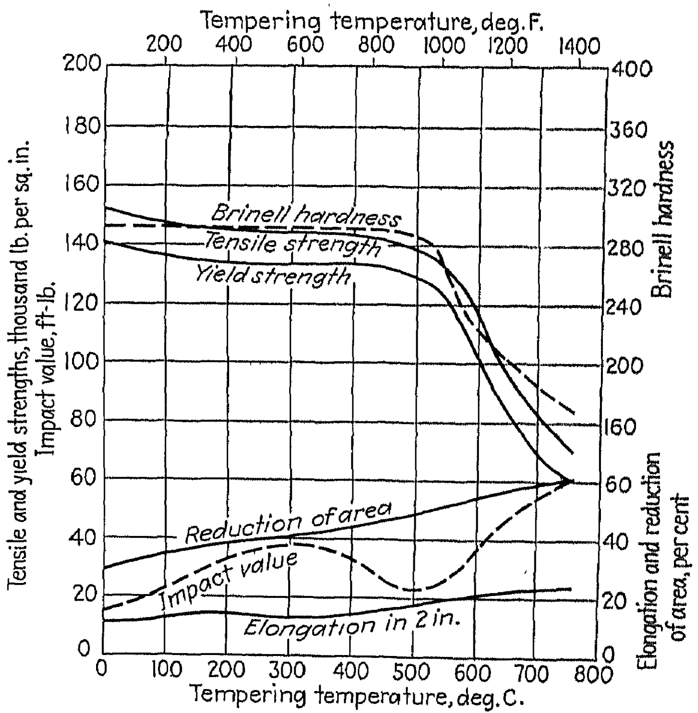

FIG. 5.—The effect of tempering on a 12.2 per cent chromium alloy quenched from 1010°C. (1850°F.). (*Giles.*(362))

41. Effect of Tempering on the Properties of Hardened High-chromium Steel.—The general effect of tempering on the mechanical properties of oil-quenched iron-chromium alloys containing 0.09 per cent carbon and 12.21, 14.02, and 15.25 per cent chromium is shown by Figs. 5 to 7, constructed by Giles.(362) All specimens were quenched from 1010°C. (1850°F.). It is to be seen that the tensile strength, yield strength, and hardness undergo sharp reduction over a relatively narrow range of tempering temperatures in the lower chromium alloys. The dip of the impact-strength curves is noteworthy, because it is characteristic of these alloys that they become relatively sensitive to shock after being tempered at certain intermediate temperatures. According to Giles, the embrittlement

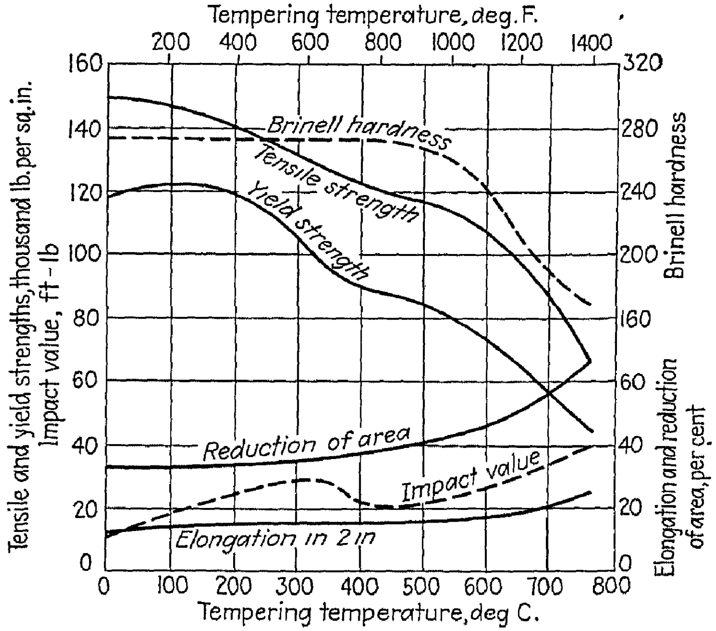

FIG. 6.—The effect of tempering on a 14 per cent chromium alloy quenched from 1010°C. (1850°F.). (*Giles* (362))

> is associated with the breaking up of the martensite and the formation of troostite. This intermediate product between martensite and granular pearlite shows its most pronounced influence in the low-chromium group.

The variation of properties with chromium content of alloys as quenched, as tempered at 540°C. (1000°F.), and as tempered at 650°C. (1200°F.) is shown in Fig. 8. With increasing tempering temperature, there is a gradual decrease of strength and a gradual increase of ductility. The most marked characteristic of the diagram for quenched steels is the rapid decline of impact strength with increased chromium content, although there is an equally rapid rise of ductility as measured by reduction of area.

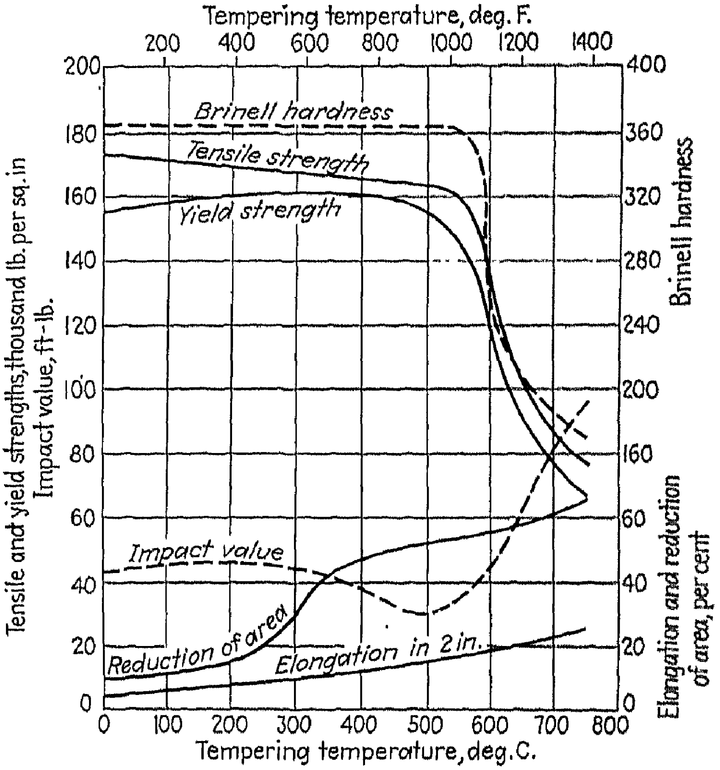

FIG. 7.—The effect of tempering on a 15.25 per cent chromium alloy quenched from 1010°C. (1850°F.). (*Giles.*(362))

In all conditions of heat treatment, toughness in impact decreases with increasing chromium content.

Properties of iron-chromium alloys as determined by various investigators are in different degrees of agreement. Those selected for comparison were reported by Aitchison,(24) Scharschu,(201) Becket,(350) Giles,(362) the Rustless Iron and Steel Corporation,(506) and the Crucible Steel Company of America.(450) Whenever possible, bands including most of the points have been drawn, as in Fig. 9 to show tensile strength. There is seemingly little change until the tempering temperature exceeds about 500°C. (930°F.). The slight upward curvature of the band

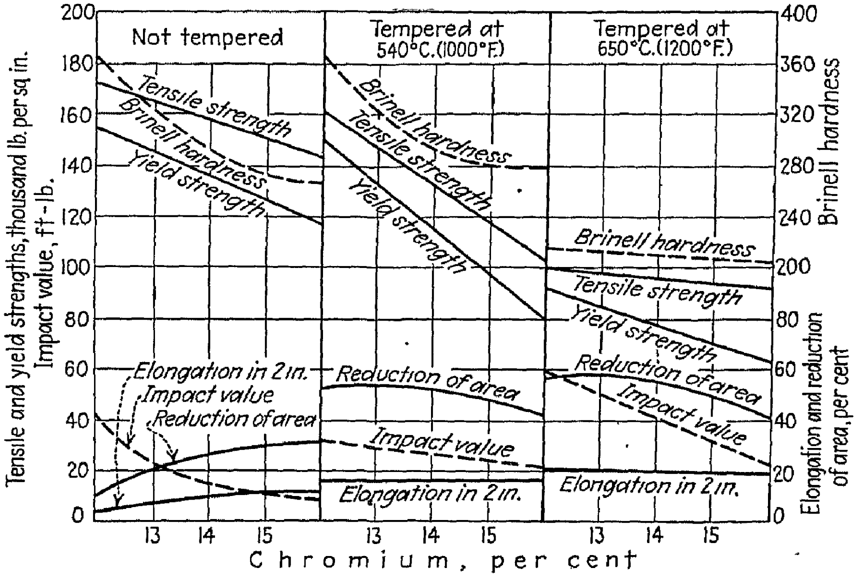

Fig. 8.—The effect of composition on quenched and tempered iron-chromium alloys. (*Giles*.[362])

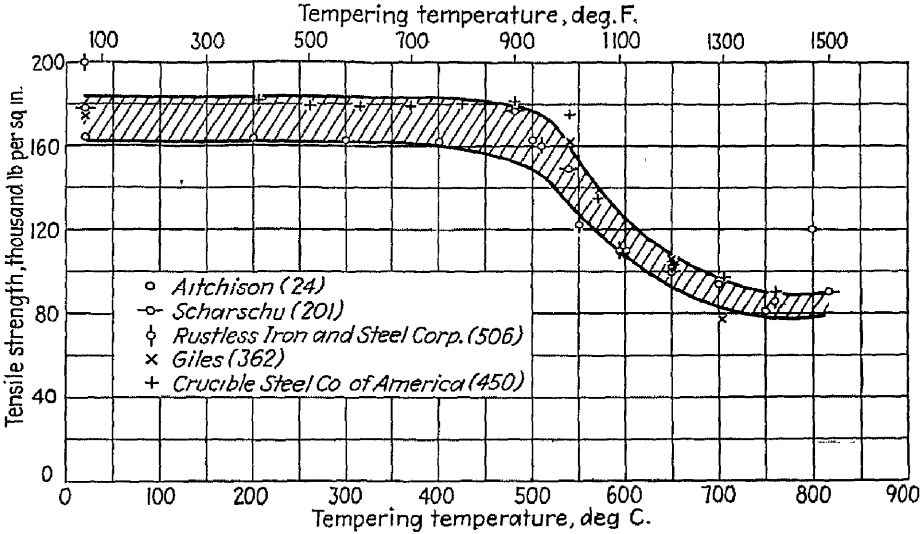

Fig. 9.—Summary of data on the tensile strength of heat-treated iron-chromium alloys.

(also very evident for hardness) at about 800°C. (1470°F.) indicates that at this temperature the lower end of the hardening range has been reached. A somewhat similar band is shown for yield strength in Fig. 10. Perhaps the most regular band of all

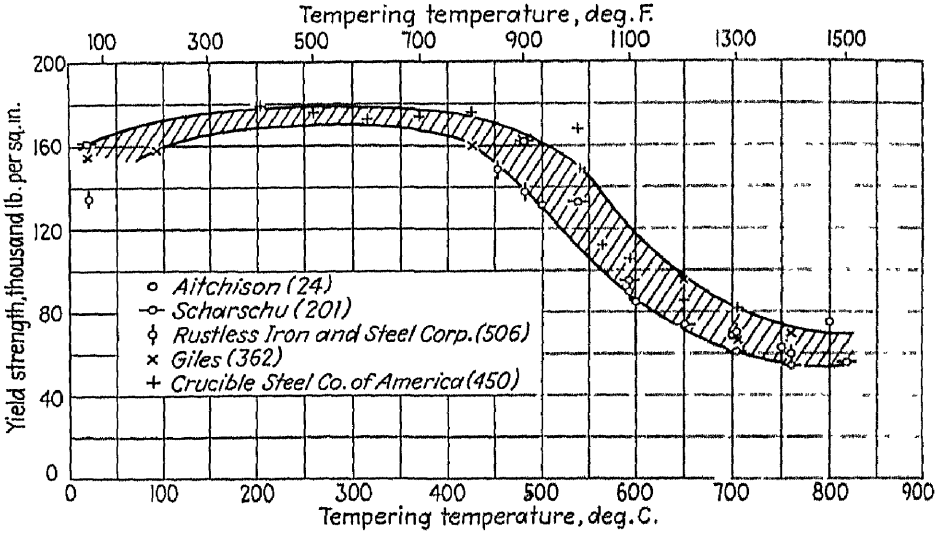

FIG. 10.—Summary of data on the yield strength of heat-treated iron-chromium alloys.

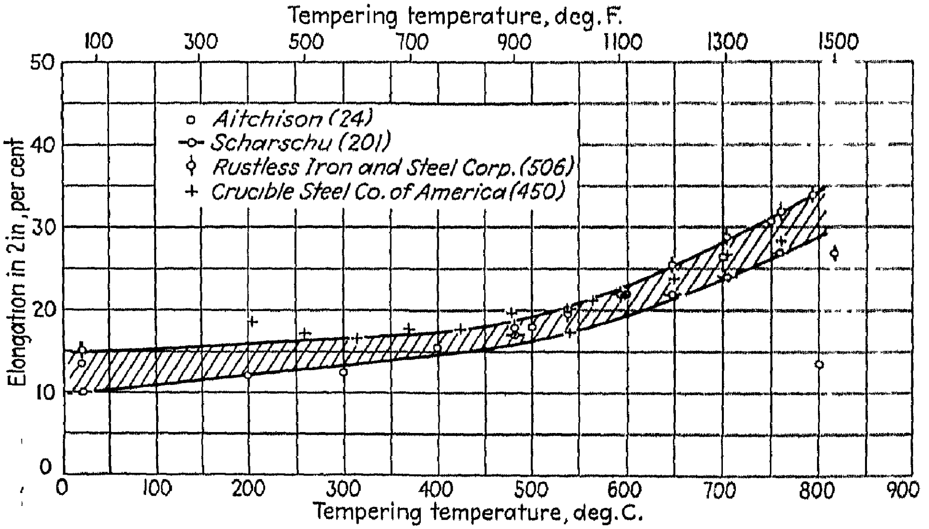

FIG. 11.—Summary of data on the elongation of heat-treated iron-chromium alloys.

is that for elongation, shown in Fig. 11. The immediate increase of elongation probably is associated with the relief of strain. The increase of slope of the band, associated with structural

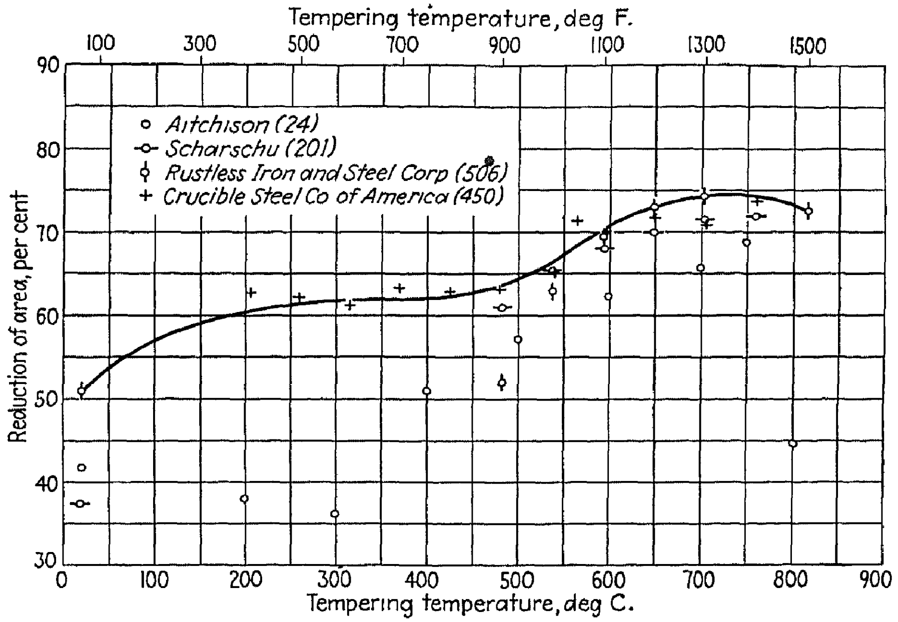

FIG. 12.—Summary of data on the reduction of area of heat-treated iron-chromium alloys.

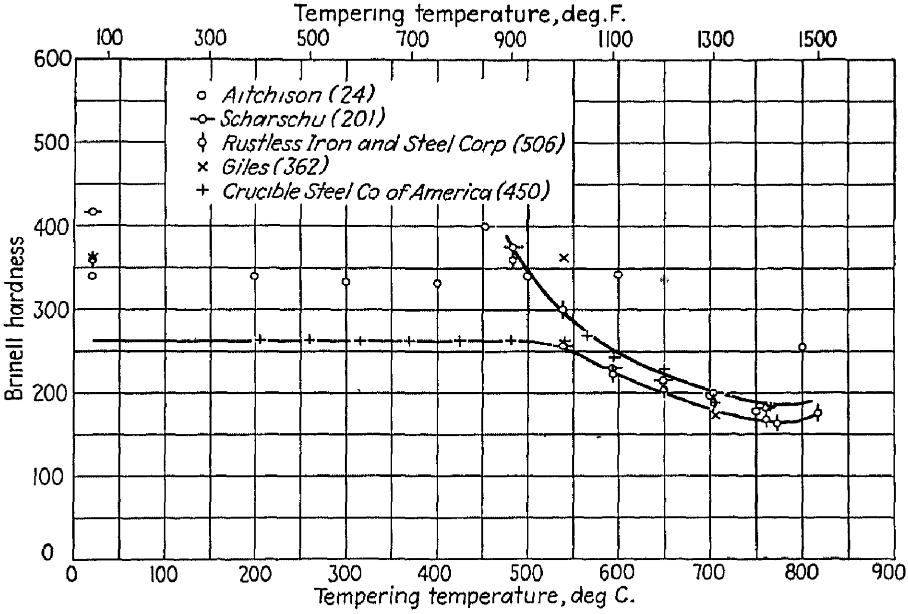

FIG. 13.—Summary of data on the Brinell hardness of heat-treated iron-chromium alloys.

change, begins at about the same temperature as that at which the drop of tensile strength is marked. Data on reduction of area, assembled in Fig. 12, are too scattered to permit the drawing of the lower boundary of the band. The line shown therefore indicates the maximum values to be expected. There is similar difficulty with Brinell hardness for tempering temperatures less than about 500°C. (930°F.) because reported values range from about 265 to over 400, as shown in Fig. 13. Agreement is relatively good at the higher tempering temperatures, however. It appears that the lowest possible hardness, about 165, results from tempering at about 775°C. (1425°F.). Three sets of impact-test data are shown in Fig. 14; all indicate minimum resistance to shock for tempering in the vicinity of 500°C. (930°F.).

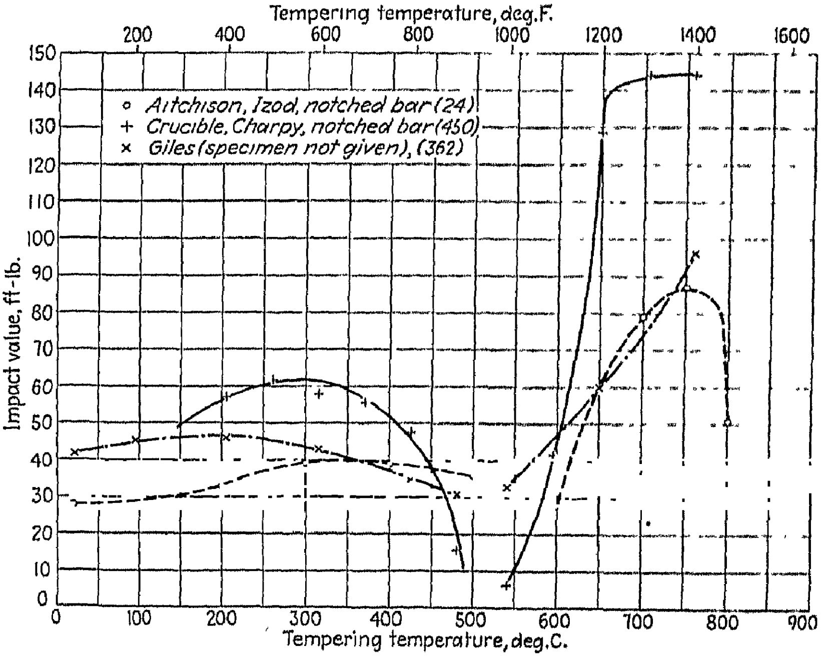

FIG. 14.—Summary of data on the resistance to impact of heat-treated iron-chromium alloys.

42. Effect of Mechanical Treatment on the Properties of Iron-chromium Alloys.—According to one manufacturer,(450) the forging of low-carbon alloys containing 10 to 14 per cent chromium should be started at 1120 to 1175°C. (2050 to 2150°F.);

it can be finished at temperatures as low as 760°C. (1400°F.). A somewhat different range is recommended by the same authority for alloys containing 15 to 18 per cent chromium; *viz.*, 1040 to 1120°C. (1900 to 2050°F.). If reheatings are necessary, it is recommended that the last one does not exceed 1040°C. (1900°F.). In general, the forging operation should be finished at a temperature between 705 and 815°C. (1300 and 1500°F.). Another manufacturer,(506) however, recommends that forging should be avoided at temperatures less than 870°C. (1600°F.). The effect of varied forging procedure on two alloys containing about 18 per cent chromium, as determined by Mochel,(74) is shown by the data of Table 7. Incidentally, the properties that resulted from the cold drawing of one specimen are noteworthy.

Low-carbon iron-chromium alloys can be cold worked without difficulty, although the resulting increase in tensile strength is less than that which results from heat treatment of the hardenable grades. According to Giles,(362) annealed ½-in. bar stock can be given a reduction of 1/16 in. without trouble. This is true

TABLE 7.—EFFECT OF MECHANICAL TREATMENT ON THE PROPERTIES OF TWO IRON-CHROMIUM ALLOYS*

Composition, per cent		Condition	Tensile strength, lb./sq in.	Yield strength, lb /sq. in.	Elastic limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
C	Cr								
0.05	17.42	As received	68,000	38,000	31,500	38.5	76.0	146	27–54
		Forged at 1065 to 900°C (1950 to 1650°F)	95,000	48,500	32,500	20.0	48.6	192	
		Forged at 1065°C. (1950°F.) to black heat	101,000	67,500	40,000	19.0	44.0	228	7
		Forged at 760°C. (1400°F) to black heat	81,500	67,000	59,000	24.0	70.3	187	9
0.12	18.24	Hot rolled	90,000	67,500	52,500	28.0	58.8	202	
		Forged at 790°C. (1450°F.) to black heat	92,000	75,500	64,000	26.0	66.3	212	28
		Forged at 1065 to 705°C. (1950 to 1300°F.)	116,500	......	43,000	13.5	19.2	223	
		Forged at 1065 to 900°C. (1950 to 1650°F)	112,500	70,000	48,000	6.0	10.4	228	
		Cold drawn	102,500	88,500	79,000	22.0	66.6	223	71

* Mochel.(74)

TABLE 8.—EFFECT OF COLD WORK ON THE PROPERTIES OF TWO IRON-CHROMIUM ALLOYS*

Chromium, per cent	Condition	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
12.21	Annealed	74,500	42,000	31	67.2	143
12.21	Reduced 1/32 in. on 1/2 in.	87,000	80,000	29	63.8	170
15.25	Annealed	76,500	40,000	32.5	72.2	147
15.25	Reduced 1/32 in. on 1/2 in.	85,800	78,000	30	68	187

* Giles.(362)

also of flats, for which a reduction of 3/32 in. in a single pass is possible. The cold-working procedure can thus be adjusted so as to result in the required final properties. The effect of cold work is illustrated by the data of Table 8. The 12.21 per cent chromium alloy, rolled to 0.020-in. strip, in the quarter-hard condition, had a Rockwell *C* hardness of 15 and a tensile strength

TABLE 9.—EFFECT OF ANNEALING ON THE TENSILE AND COMPRESSIVE PROPERTIES OF A COLD-DRAWN ALLOY CONTAINING 0.12 PER CENT CARBON AND 12 PER CENT CHROMIUM*

Annealed 1 hr. at		Tensile properties					Compressive properties	
°C.	°F.	Tensile strength, lb./sq. in.	Elastic limit, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Elastic limit, lb./sq. in.	Yield point, lb./sq. in.
...	. .	83,000	15,700	71,600	28.5	70	20,200	62,800
100	210	83,000	17,900	71,600	28	70	20,200	62,800
200	390	84,200	31,400	72,800	27	70	26,000	60,400
300	570	85,100	49,300	74,000	24	69	40,300	67,200
375	705	76,100	49,300	58,200	32	73	44,800	58,200
450	840	76,100	42,500	58,200	32	72	42,600	58,200
650	1200	73,400	40,600	44,800	37	74	45,800	47,000

* Rees.(42)

of 115,000 lb. per sq. in. In the fully hardened condition, its hardness was 44*C* and its tensile strength was 175,000 lb. per sq. in. The material could be cold rolled or drawn to a tensile strength of as much as 190,000 lb. per sq. in.; in this condition, the modulus of elasticity was 28 million lb. per sq. in., and the modulus of rigidity was 11.2 million lb. per sq. in.

The effect of annealing on the properties of ¾-in. rods, "cold drawn, ground, and polished," of an alloy containing 0.12 per

TABLE 10.—MECHANICAL PROPERTIES OF LOW-CARBON SHEET CONTAINING 15 TO 18 PER CENT CHROMIUM*

Thickness, in.	Tensile strength, lb./sq in.	Yield strength, lb./sq. in.	Elongation, per cent, in			Rockwell *B* hardness
			2 in.	4 in.	8 in.	
Hot rolled, annealed, and pickled						
0.01875	75,000	55,500	22	20	15	79
0.025	72,700	41,900	27	20	16	81
0 03125	73,400	44,500	29	22	17	79
0 0375	74,900	50,500	29	22	17	81
0 05	74,800	48,100	31	24	19	78
0.0625	74,200	54,100	30	23	18	82
0 0781	81,700	55,000	26	21	17	84
0 1093	77,100	50,100	28	22	18	82
0 1406	73,100	46,900	33	27	20	80
0 1718	71,300	51,100	35	27	20	79
0.25	71,900	44,500	34	27	20	79
0.5	71,000	44,100	38	30	21	80
Cold rolled, one pass						
0.0375	77,000	54,000	26	20	15	83
0.05	78,500	53,100	29	22	17	83
0 0871	82,000	63,000	27	21	16	84
Annealed, pickled, and polished						
0 01875	76,600	59,100	20	17	13	81
0 025	75,400	51,100	27	20	15	82
0 0375	78,100	57,700	27	20	15	83
0.0625	76,000	57,900	28	22	17	83
0 0781	84,500	67,700	27	20	15	84
0 1406	78,400	62,900	29	22	16	82

* Johnson.(372)

cent carbon and 12 per cent chromium, as determined by Rees,(42) is shown by the data of Table 9. Annealing in the 300 to 375°C. (570 to 710°F.) range caused marked increase of the elastic limit, as is true of carbon steels.

43. Sheet and Strip Containing 15 to 18 Per Cent Chromium.—The carbon content of the 15 to 18 per cent chromium steels is usually kept below 0.12 per cent. This results in the greatest ductility after low-temperature annealing. Properties of these steels are like those of carbon steel in that the gage has a definite effect on ductility; the heaviest gage has the greatest elongation. According to Johnson,(372) elongations are usually reported on 2-, 4-, and 8-in. gage lengths. The data of Table 10 are for specimens usually cut in the direction transverse to that of rolling. Data on longitudinal strip specimens are given in Table 11. These steels are capable of continuous service at 790°C. (1450°F.) and intermittent service at 845°C. (1550°F.). Temperatures ranging from 470 to 495°C. (875 to 925°F.) should be avoided, or care must be exercised because of the brittleness of these steels when cold, induced by previous heating for long periods within this range..

TABLE 11.—MECHANICAL PROPERTIES OF LONGITUDINAL SPECIMENS OF STRIP CONTAINING 0.09 PER CENT CARBON AND 16.53 PER CENT CHROMIUM*

Thickness, in.	Condition	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation, per cent, in			Rockwell *B* hardness
				2 in.	4 in.	8 in.	
0.180	Hot rolled	132,600	104,500	12	7.5	4.5	103
0 180	Annealed	70,000	49,300	31	23	20	82.5
0.075	Hard	116,500	112,100	6	3.5	2	105
0.075	Soft	78,300	53,400	25	22	16.5	84
0.047	Hard	110,800	106,500	4	2.5	1	102
0.047	Soft	74,000	46,400	30	24	20	78
0.031	Hard	112,100	106,900	3	1.5	1	98
0 031	Soft	71,100	47,400	30	25	20	78

* Johnson.(372)

44. Endurance Limits of Low-carbon Iron-chromium Alloys.—Endurance limits and endurance ratios, as reported by McAdam,(48,117) Moore,(51) Mochel,(74) and Speller, McCorkle, and Mumma,(128) are collected in Table 12. Endurance limits of at least half of the tensile strength seem easily possible with suitable heat treatment.

TABLE 12.—ENDURANCE LIMIT OF SOME IRON-CHROMIUM ALLOYS

Investigator	Composition, per cent		Quenching temperature		Tempering temperature		Tensile strength, lb./sq in.	Endurance limit, lb./sq. in.	Endurance ratio	Kind of test
	C	Cr	°C	°F.	°C	°F.				
McAdam(48)..	0.08	11.78	980	1800	480	900	166,500	74,000	0.45	Rotating cantilever
					540	1000	164,600	78,000	0.47	
					595	1100	109,500	61,000	0.56	
					705	1300	83,300	45,000	0.54	
			Furnace cooled				63,300	31,000	0.49	
Mochel(74).. .	0.08	11.10	Not stated		.	..	156,000	92,000	0.58	Rotating beam
	0.08	14.26	Not stated		.	. .	70,400	46,700	0.66	Rotating beam
	0.07	12.67	Not stated			..	121,000	62,000	0.51	Rotating cantilever
	0.07	12.67	Not stated		...	....	121,000	68,000	0.56	Non-rotating cantilever
McAdam(117)	0.11	12.71	980	1800	650	1200	. . .	50,000	.	Rotating cantilever
Speller, Mc-Corkle, and Mumma(128)	0.07	18.56	As rolled				76,500	45,000	0.59	
Moore(51)..	0.03	13.47	As rolled				82,400	40,000	0.42	Rotating beam

Several steels, including one stainless iron, were tested by Russell and Welcker(199) at −40°C. (−40°F.). All showed increased endurance limit, tensile strength, and hardness, as compared with room-temperature values, although the stainless alloy (containing 0.07 per cent carbon and 13.85 per cent chromium) was relatively brittle in impact.

45. Corrosion Endurance.—Since the high-chromium steels are often used under conditions that include exposure to steam, the results of Fuller,(179) given in Table 13, are of interest. His tests were made on an alloy containing 0.1 per cent carbon and 12.5 per cent chromium, heat-treated to produce three sets of mechanical properties. The first group, of lowest tensile strength, showed appreciable reduction of endurance limit with increasing temperature, whereas the intermediate group showed little loss in fatigue resistance up to at least 370°C. (700°F.). The precorroded specimens showed no damage by stressless corrosion.

TABLE 13.—THE CORROSION FATIGUE OF A STEEL CONTAINING 0.1 PER CENT CARBON AND 12.5 PER CENT CHROMIUM, VARIOUSLY HEAT TREATED*

Tensile strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Conditions of test	Endurance limit, lb./sq. in.
71,000	33,000	37	74	201	Air; room temperature	34,000
					Steam, 60 lb.; 150°C. (300°F.)	29,000
					Steam, 220 lb.; 370°C. (700°F.)	20,000
102,000	63,000	26	70	219	Air; room temperature	61,000
					Steam jet in the atmosphere	33,000
					Steam and air in box; 75°C. (170°F.)	52,000
					Steam, atmospheric pressure, 100°C. (210°F.)	54,000
					Steam, 60 lb.; 150°C. (300°F.)	55,000
					Steam, 140 lb.; 180°C. (355°F.)	54,000
					Steam, 220 lb.; 370°C. (700°F.)	54,000
102,000	63,000	26	70	219	Precorroded 1 week in wet steam and air; air; room temperature	61,000
					Steam jet in atmosphere	34,000
					Steam, atmospheric pressure; 100°C. (210°F.)	54,000
					Steam, 60 lb.; 150°C. (300°F.)	54,000
116,000	80,000	21	66	236	Air; room temperature	56,000
					Steam; 60 lb.; 150°C. (300°F.)	54,000

* Fuller (179)

The behavior of the highest tensile-strength group was similar to that of the intermediate group.

Tests in which corrosion was accomplished by aqueous solutions, conducted by Speller, McCorkle, and Mumma,(128) indicated that the endurance limit is decreased as the chloride concentration is increased. An alloy containing 0.07 per cent carbon and 18.56 per cent chromium, as rolled, had an endurance limit of 45,000 lb. per sq. in. when tested in air (specimen coated with petrolatum). This was reduced to 38,000 lb. by running in synthetic Pittsburgh tap water, and to 36,000 lb. by localized corrosion in the synthetic tap water. Investigation of corrosion fatigue was extended to repeated and to fluctuating stresses by Gough and Sopwith.(453) The materials tested included a steel containing 0.12 per cent carbon and 14.75 per cent chromium. After heat treatment, consisting of quenching from 950°C. (1740°F.) and tempering at 650°C. (1200°F.), tests were made in air and in 3 per cent salt solution. As is true of corrosive conditions combined with reversed stress, no endurance limit was found when the salt spray was used; the log *S*–log *N* curve declined continuously.

Alloys in the form of "streamline" wire were tested by Haven:(228) the somewhat inconclusive results are subjoined:

Composition, per cent			Tensile strength, lb. per sq. in.	Torsional endurance limit, lb. per sq. in.	Carbonate water torsional endurance limit, lb. per sq. in.
C	Cr	Ni			
0.09	12.63	0 53	145,900	36,500	18,000
0.10	18 34	. . .	116,600	35,000	27,500

46. Effect of Temperature on Tensile Properties.—Temperatures down to −40°C. (−40°F.) have little effect on the tensile properties of low-carbon iron-chromium alloys containing 10 to 13.5 per cent chromium, according to the data of Table 14, given by a manufacturer.(506) This fact makes the material valuable for use in refrigerating equipment.

The effect of elevated temperatures on the short-time tensile and creep strengths of alloys containing 16 to 20 per cent chro-

TABLE 14.—PROPERTIES OF IRON-CHROMIUM ALLOYS CONTAINING A MAXIMUM OF 0.12 PER CENT CARBON AND 10 TO 13.5 PER CENT CHROMIUM AT SUBZERO TEMPERATURES*

Property	Temperature	
	20°C. (70°F.)	−40°C. (−40°F.)
Tensile strength, lb. per sq. in.	75,000	77,000
Elongation in 2 in., per cent	34	30
Brinell hardness	140	150
Izod impact, ft-lb	115	80
Endurance limit, lb. per sq. in.	45,000	48,000

* Rustless Iron and Steel Corporation.(596)

mium is indicated by the bands shown in Fig. 15, which was constructed from data of Krivobok.(499)

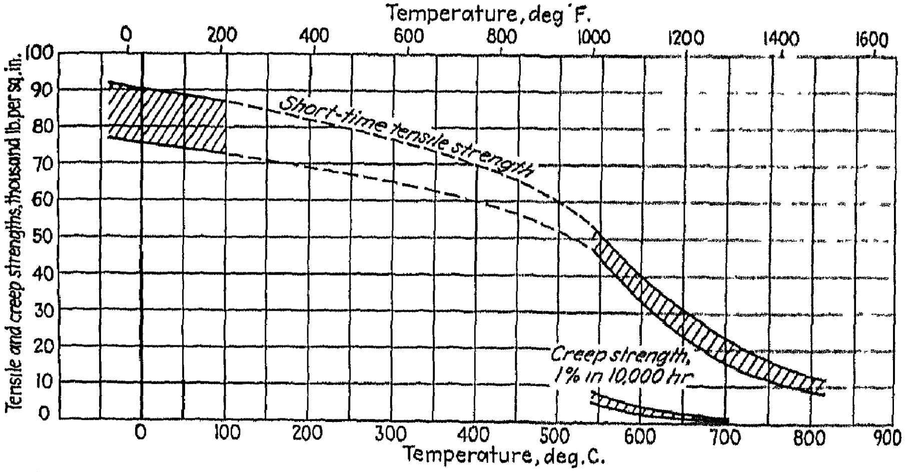

FIG. 15.—The effect of temperature on the tensile and creep strengths of low-carbon alloys containing 16 to 20 per cent chromium. (*Based on data of Krivobok.*(499))

Earlier creep data, obtained when necessary conditions of test and interpretation were even less well known, were reported, among others, by Monypenny,(50) McVetty and Mochel,(92) Clark and White,(110) and Kanter and Spring.(148) However, it seems best to concentrate on the kind of data currently—although perhaps ephemerally—in favor. For general discussion of the matter, reference is made to "Compilation of Available

High-temperature Creep Characteristics of Metals and Alloys"(487) and to Gillett,(521) since it is here out of place to review the limitations and uses of numerical values.

Alloys containing 0.11 per cent carbon, 2.8 per cent nickel, and 12.5 per cent chromium, and 0.13 per cent carbon and 13.4 per cent chromium, were tested by Coffin and Swisher.(216) Results, in terms of stress for a flow rate of 1 per cent per 100,000 hr. at 450°C. (840°F.), were respectively 2400 (almost certainly a misprint for 12,400) and 12,200 lb. per sq. in. These data are in fair agreement with those of Johnson(372) shown in Fig. 16.

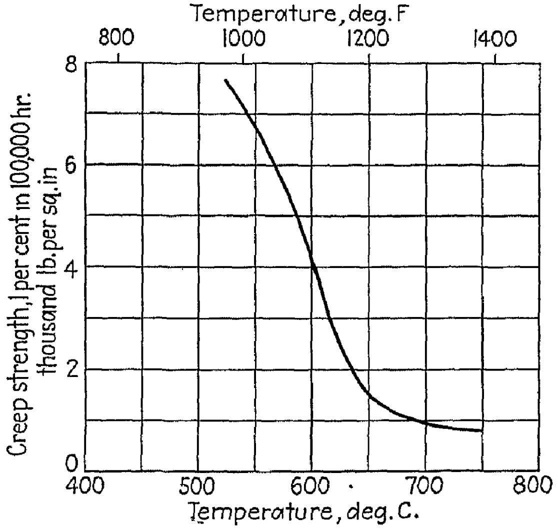

FIG. 16.—The creep strength (1 per cent elongation in 100,000 hr.) of low-carbon 14 to 18 per cent chromium alloys. *(Plotted from data quoted by Johnson.(372))*

The latest and most complete data on creep of low-carbon 12 to 18 per cent chromium alloys are given in the aforementioned "Compilation"; but even they do not permit rigorous generalization. Data taken from the summarizing graphs for stress for a rate of creep of 0.1 per cent in 1000 hr. are plotted in Fig. 17 as log stress versus reciprocal absolute temperature. It will be noted that there is some justification for a linear relation at temperatures below about 700°C. (1290°F.). However, this means of plotting was selected merely to facilitate interpolation; whether it has any other justification is unknown.

47. Variation of Resistance to Impact with Chromium Content. It was shown by Krivobok(378) that the resistance to impact at room temperature of a series of iron-chromium alloys underwent sharp decline when the chromium content exceeded about 15 per cent. This behavior was found to be independent of heat treatment and of carbon content; it was not reflected by tensile properties, however. Similar results were found for welded specimens by Hodge,(307) although in this instance the lowest chromium content was about 14 per cent, *i.e.*, near the lower end of the brittle range. It is suggested that the phenomenon is analogous to that encountered in electric sheet(272) and consequently does not require the postulation of a new phase, or some such explanation. High-purity iron itself is brittle below a certain temperature. Both iron and electric sheet recover their toughness upon heating; the change occurs abruptly—and, in electric sheet, the temperature of change increases with increased silicon content. Data of Sergeson(204) and of Krivobok(378) show that this is likewise true for increasing chromium content in iron-chromium alloys. There are not enough data to construct a temperature-composition curve, but it can be stated that the transition from brittle to tough is below room temperature at 13 per cent chromium and well above room temperature at 18 per cent. This suggests that compositions adjudged, on the

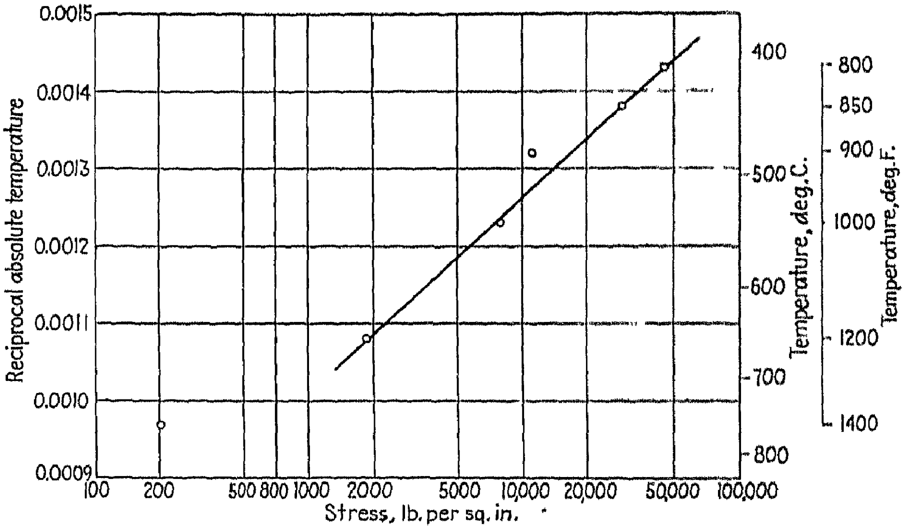

FIG. 17.—Creep stress for a rate of 0.1 per cent in 1000 hr. plotted as log stress versus reciprocal absolute temperature for low-carbon 16 to 18 per cent chromium alloys.(487)

basis of room-temperature tests, to be too brittle for service involving impact would be suitable at certain elevated temperatures. This has been verified by practical experience.

B. MECHANICAL PROPERTIES OF MODIFIED IRON-CHROMIUM ALLOYS

When the chromium content of the low-carbon alloys is increased from about 12 or 14 to around 16 or 18 per cent, the corrosion resistance of the alloys in many media is increased, but the alloys can no longer be hardened appreciably by heat treatment. Additional elements are, therefore, frequently added to increase hardenability.

48. Effect of Nickel.—The addition of small percentages of nickel to the low-carbon 10 to 14 per cent chromium steels increases their air hardenability. This is accomplished without great loss of toughness and corrosion resistance. The former is illustrated by the data of Table 15 obtained by Monypenny.(191)

Table 15.—Influence of Nickel on Low-carbon 13 Per Cent Chromium Steel, Air Hardened from 950°C. (1740°F.) and Water Quenched from 700°C. (1290°F)*

Composition, per cent			Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness		Izod impact, ft-lb.
C	Cr	Ni					Hardened	Tempered	
0 09	13 7	0.10	83,000	66,400	32.5	68.8	241	179	100 96 106
0 08	13 3	0.46	91,200	77,000	32.0	68 8	340	217	98 98 101
0 08	13.6	0.80	100,200	87,500	29 0	63.7	351	241	86 86 88
0 10	14.1	1.23	104,500	89,900	25 5	55 8	418	255	65 62 65

* Monypenny.(191)

According to Monypenny, it depends upon the type of article to be produced whether or not such additions are advantageous, since the cross-section of the piece heat treated is important. In large bars or forgings, about 1 per cent nickel may facilitate heat treatment consisting of quenching and tempering. In small pieces, on the other hand, the presence of such amounts of nickel may be disadvantageous, since there is increased danger of cracking during cooling after rolling or forging. Air hardening induced by nickel is especially noticeable in low-carbon alloys containing about 4 per cent nickel; consequently, this element is undesirable if soft material is required; a nickel content of 1 per cent is about the limit.

It has been recommended, according to Mochel,(383) that springs which must resist corrosion be made of steel containing a maximum of 0.12 per cent carbon, 13 per cent chromium, and 2 per cent nickel. The material is best cold rolled or drawn from annealed bars or strips to the required tensile strength.

Small percentages of nickel also enable the relatively nonhardenable 15 to 18 per cent chromium steels to be hardened by heat treatment. Such amounts are not detrimental to resistance to corrosion. The effect of heat treatment on an alloy containing 18 per cent chromium and 2 per cent nickel, determined by Barnaby,(340) is shown by the data of Table 16. This steel had the resistance to corrosion of the corresponding alloy without nickel, was responsive to heat treatment, and had good resistance to impact. (Monypenny(191) described similar alloys, known as "twoscore steels" in Great Britain.) High strength can be obtained in the steels of this group containing 1 to 2 per cent nickel, if the chromium content is limited to about 16 per cent; data on these 16-1 steels are given in Table 17.

TABLE 16.—PROPERTIES OF AN ALLOY CONTAINING 0.09 PER CENT CARBON, 17.8 PER CENT CHROMIUM, AND 2.08 PER CENT NICKEL, QUENCHED FROM 950°C. (1740°F.) IN THE FORM OF 1⅛-IN. RODS*

Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Brinell hardness	Izod impact, ft-lb.
°C.	°F.					
400	750	132,000	111,000	20	269	79 60 61
500	930	129,700	103,000	22	265	96 88 88
600	1110	96,800	77,000	28.5	225	86 75 94
650	1200	95,200	72,500	30	217	84 86 88
700	1290	100,000	....	28	231	83 83 80
750	1380	104,200	....	27.5	241	81 79 77

* Barnaby.(340)

Other data are reproduced in Table 18. The 2 per cent nickel steels have the best combination of properties when the chromium content is between 17 and 18 per cent. Evidently too much austenite is formed with 3 per cent nickel; even though the material has high strength, it is difficult to soften by tempering, and, when softened, it shows relatively low toughness; this is probably connected with the retained austenite and its subsequent phase change.

TABLE 17.—MECHANICAL PROPERTIES OF 16-1 STEELS OIL QUENCHED FROM 950°C. (1740°F.) AND TEMPERED AS SHOWN

Composition, per cent			Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	*Elongation* in 2 in., per cent	Reduction of area, per cent	Brinell hardness
C	Cr	Ni	°C.	°F.					
0.11	16.55	1.12	.	....	....	......	..	..	364
0.11	16.55	1.12	450	840	174,000	145,300	16	48	364
0.11	16.55	1.12	525	975	166,000	128,000	20	53	311
0.11	16.55	1.12	750	1380	113,000	84,000	26	58	196
0.08	16.20	2.19	..		.... .	.... .	.	..	364
0.08	16.20	2.19	525	975	158,000	127,000	22	56	302

49. Effect of 1 Per Cent Copper.—The addition of copper changes response to heat treatment, tensile properties, and resistance to corrosion. Experiments with low-carbon 13 per cent chromium steels, according to Parker,(389) have indicated that 1 per cent copper is the most advantageous amount; this concentration does not materially change the hot-rolling or forging properties and is beneficial from the standpoint of resistance to corrosion.

So far as hardenable alloys are concerned, copper addition results in more uniform response to heat treatment. Further, copper leads to greater hardness after quenching. Tempering temperatures should be 10 to 55°C. (20 to 100°F.) higher for alloys containing 1 per cent copper than for copper-free alloys to produce the same hardness and tensile strength.

Figure 18 shows data obtained on a heat-treated alloy containing 0.12 per cent carbon, 13.24 per cent chromium, and 1.11 per cent copper. Before tempering, the bars were hot rolled to 1-in. rounds, then cooled in air. Noteworthy results are the high tensile strength in the air-quenched condition, the secondary

TABLE 18.—PROPERTIES OF 16 TO 18 PER CENT CHROMIUM STEELS CONTAINING 2 TO 3 PER CENT NICKEL, OIL QUENCHED FROM 950°C. (1740°F.) AND TEMPERED AS SHOWN*

Composition, per cent			Tempering			Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness
			Temperature		Time, hr.						
C	Ni	Cr	°C.	°F.							
0.10	2.19	16.20	525	975	1.5	148,000	127,000	16	54	19	302
			750	1380	3	....	....	..	..	41	269
0.10	3.06	16.24	525	975	1	171,000	150,000	16	55	30	302
			750	1380	3	....	....	..	..	51	277
0.10	2.14	17.28	525	975	1	156,000	124,000	19	60	40	311
			750	1380	3	....	....	..	..	62	241
0.10	3.22	17.10	525	975	1	155,000	130,000	19	60	44	302
			750	1380	3	....	....	..	..	45	269
0.08	2.10	18.11	525	975	1	165,000	131,000	20	53	48	302
			750	1380	3	....	....	..	..	64	228
0.12	3.17	18.37	525	975	1	175,000	122,000	15	50	22	311
			750	1380	3	....	....	..	..	22	203

* The samples were furnace cooled from 750°C. (1380°F.) and air cooled from 525°C. (975°F.).

hardening upon tempering at 510°C. (950°F.), the sluggish response to tempering, and the unusual behavior of the proportional limit for tempering temperatures less than 565°C. (1050°F.). Parker explained this behavior as follows: At a tempering temperature of 205°C. (400°F.) the steel retains some austenite and is in a condition of strain from rolling and air hardening. At 370°C. (700°F.), part of the strain is relieved, which increases the elastic ratio. At 510°C. (950°F.), the residual austenite is transformed to martensite, which increases hardness and increases strain (*cf.* the impact values). From 510 to 565°C. (950 to 1050°F.), the martensite decomposes to a structure typical of low-carbon iron-chromium alloys at these temperatures, characterized by comparatively low elastic ratio, impact resistance, and corrosion resistance. At higher temperatures, the structure is stable and the properties are normal.

Other data were given by Saklatwalla and Demmler,(124) who found that small copper additions produced a definite hardening effect on the low-carbon 12 per cent chromium steels. Monypenny(191) showed that 1.2 per cent slightly increased the hardness. He also added 5 and 10 per cent copper to 14 and 16 per cent chromium steels and found that, unlike nickel, copper did not lead to the production of an austenitic steel. Later, according to Lippert,(467) Digby tested low-carbon 15 and 18 per cent chromium steels containing 8 to 10 per cent copper and found them to be ferritic rather than austenitic; the steels consisted of two phases, of which one was high in copper, the other in iron

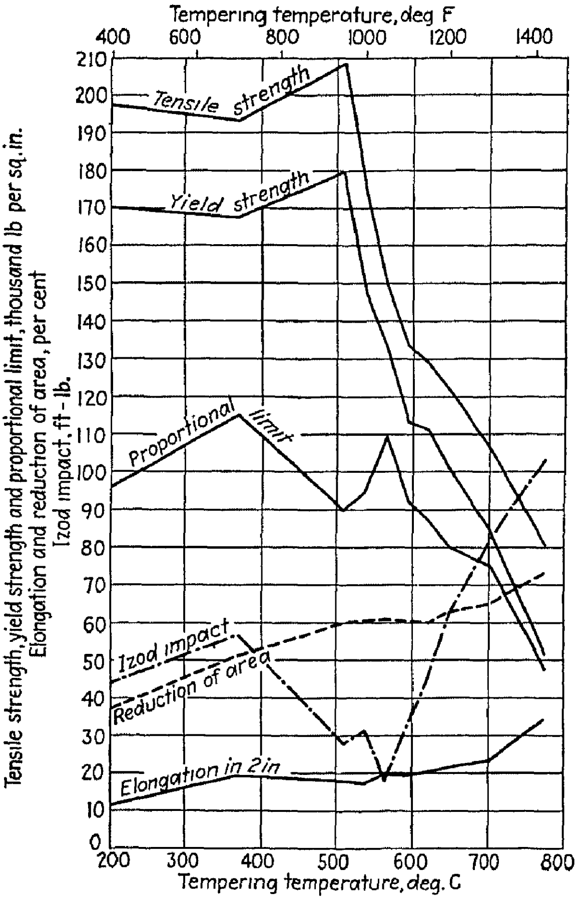

FIG. 18.—Mechanical properties of an alloy containing 0 12 per cent carbon, 13.24 per cent chromium, and 1.11 per cent copper, hot rolled, air cooled, and tempered as shown. (*Based on data of Parker.*(389))

content. The high-copper phase was named the "cypritic constituent"; it was found to melt at about 1050°C. (1925°F.), which made it necessary to hot forge the steels below 1040°C. (1900°F.). The results of tests on heat-treated sections of hot-worked steels are given in Table 19.

TABLE 19.—MECHANICAL PROPERTIES OF AIR-COOLED AND TEMPERED LOW-CARBON CHROMIUM-COPPER STEELS*

Property	18 per cent chromium, 8 to 10 per cent copper	15 per cent chromium, 8 to 10 per cent copper
Tensile strength, lb. per sq. in. . .	95,000 to 105,000	130,000 to 180,000
Yield strength, lb. per sq. in. . . .	72,000	110,000 to 120,000
Elongation in 2 in., per cent. . . .	29	21 to 22
Reduction of area, per cent.	57	50 to 55
Brinell hardness.	250 to 260	300 to 315
Izod impact, ft-lb.	66	50 to 120

* Digby, according to Lippert.(467)

50. Effects of Copper Plus Silicon.—According to DeVries,(355) low-carbon 16 per cent chromium steels containing 1 per cent each of silicon and copper can be forged and rolled with fair reliability. The recommended preheating schedule for a common composition is to soak at 815°C. (1500°F.), then raise the temperature to a maximum of 1150°C. (2100°F.) at a rate of 1 hr. per in. Hot work should be stopped at 815°C. (1500°F.). Six-inch strips of this steel, fabricated according to the best practice, had

TABLE 20.—MECHANICAL PROPERTIES OF STEEL STRIP CONTAINING 0.08 PER CENT CARBON, 16.08 PER CENT CHROMIUM, 0.75 PER CENT SILICON, AND 1.13 PER CENT COPPER, AFTER AIR COOLING FROM TEMPERATURES SHOWN*

Thickness, in.	Air cooled from		Tensile strength, lb. per sq. in.	Elongation in 2 in., per cent	Elongation in 4 in., per cent
	°C.	°F.			
0.038	815	1500	78,000	36.5	28.7
0.018	800	1475	78,000	32.0	24.0

* DeVries.(355)

the mechanical properties shown in Table 20. The short-time high-temperature tensile tests shown in Table 21 indicate that such alloys have considerable elongation and fairly high tensile strength at hot-rolling temperatures.

TABLE 21.—SHORT-TIME HIGH-TEMPERATURE PROPERTIES OF AN ALLOY CONTAINING 0.06 PER CENT CARBON, 14.52 PER CENT CHROMIUM, 0.98 PER CENT COPPER, AND 0.78 PER CENT SILICON*

Testing temperature		Tensile strength, lb. per sq. in.	Yield strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
°C.	°F.				
980	1800	6650	5050	60	69.5
1040	1900	4625	3250	60.2	73.7
1095	2000	3700	2550	60	80

* DeVries.(355)

The machinability of iron-chromium alloys is improved by the addition of copper and silicon, especially when the material is heat treated by air or oil quenching. These alloys work harden slowly; consequently they may be rolled to sheet and drawn to wire with ease. They can also be upset and formed, and in the annealed condition they can be spun, rolled, flanged, and bent.

Low-carbon non-hardenable iron-chromium alloys are characterized by relatively low tensile strength (in all conditions except the drastically cold-worked) and low elastic ratio. Copper and silicon additions partly rectify these deficiencies. Mechanical properties of four such alloys in various conditions of heat treatment are given in Table 22.

51. Effect of Molybdenum.—About 0.5 per cent molybdenum is sometimes added to the low-carbon 12 to 15 per cent chromium steels to improve grain size, forging, rolling, pickling, and machinability. Molybdenum also imparts desirable non-seizing properties. Mochel(74) mentioned the use of large quantities of such alloys. Monypenny(191) supplied data which show that 0.97 per cent molybdenum in a steel containing 0.08 per cent carbon, 13.20 per cent chromium, and 0.80 per cent nickel raised the transformation temperature and reduced the air-hardening capacity. An 18 per cent chromium steel containing 1.5 to 2 per cent molybdenum was cited by Maurer(469) as being highly resistant to corrosion and having improved weldability as compared with the molybdenum-free steel.

52. Effect of Tungsten.—Steel containing 0.12 per cent maximum carbon, 12 to 14 per cent chromium, and 2.5 to 3.5 per cent tungsten has been proposed for oil-cracking service. This material is said to have higher useful strength as elevated temperatures than similar material containing no tungsten, but no data are available.

TABLE 22.—MECHANICAL PROPERTIES OF LOW-CARBON 12 TO 16 PER CENT CHROMIUM ALLOYS CONTAINING COPPER AND SILICON*

Composition, per cent				Quenching temperature		Quenching medium	Tempering temperature		Tensile strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
C	Cr	Si	Cu	°C.	°F.		°C.	°F.					
0.12	12.50	1.18	1.15	925	1700	Oil	425	800	180,000	135,000	16.5	56.8	
				955	1750	Air	425	800	207,100	140,000	16.5	57.5	
0.08	15.85	0.82	1.35	925	1700	Water	540	1000	142,800	64,500	21	61.5	
				925	1700	Oil	650	1200	103,000	57,500	25	63.5	
0.05	15.40	0.78	1.00	Hot rolled		Air	540	1000	109,200	60,000	27	67.5	
				790	1450	Air	...	....	77,000	50,400	35.5	75.5	
				790	1450	Air	205	400	76,400	50,300	35.2	76.4	
				790	1450	Air	540	1000	92,000	60,000	30	71.7	
0.08	16.56	0.73	0.94	815	1500	Air	...	....	78,200	45,000	44	68.2	163
				845	1550	Water	...	....	82,500	52,900	39	66.8	163
				845	1550	Oil	675	1250	82,100	55,000	34	71.9	170
				815	1500	Air	730	1350	77,400	48,400	40.5	74.3	166

* DeVries.(355)

Heat-treated low-carbon 13 per cent chromium steels containing tungsten retain their hardness better after long heating at 500°C. (930°F.) than similar steels containing nickel or molybdenum and those containing no added element. This is shown in the following data obtained recently by Scharschu:*

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* C. A. Scharschu, private communication, June 2, 1939.

Held at 500°C. (930°F.), hr.	Brinell hardness of material containing			
	No additional element	2.5 per cent Ni	3.5 per cent W	1.2 per cent Mo
Quenched	337	411	344	388
30	..	276	341	331
47	319			
825	215	229	285	262
10,000	184	200	294	250

The base material contained 0.08 to 0.13 per cent carbon and 12.9 to 13.3 per cent chromium; the specimens were air cooled from 955°C. (1750°F.) before the treatment at 500°C. (930°F.). The hardness loss of the tungsten-bearing material was only 14 per cent compared with 50, 46, and 36 per cent for the materials containing nickel, no added element, and molybdenum in the order given.

53. Effect of Nitrogen.—The hardenability of low-carbon 10 to 18 per cent chromium steels is greatly increased by the addition of nitrogen. (The nitrogen is added conveniently in the form of ferrochromium containing about 70 per cent chromium and 0.7

TABLE 23.—INFLUENCE OF NITROGEN ON THE LOW-CARBON 11 TO 14 AND 15 TO 18 PER CENT CHROMIUM STEELS*

Composition, per cent			Oil quenched from		Tempered at		Tensile strength, lb./sq. in.	Yield strength, lb./sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness
C	Cr	N	°C.	°F.	°C.	°F.						
0.07	13.44	0.025	950	1740	.	.	151,000	139,000	10	15	5	293
0.07	13.44	0.025	950	1740	600	1110	95,500	66,000	23	60	58	187
0.07	13.44	0.025	...	....	750	1380	78,500	44,000	30	71	101	137
0.07	13.19	0.08	950	1740			194,000	178,000	5	11	4	402
0.07	13.19	0.08	950	1740	600	1110	123,500	106,500	21	65	60	228
0.07	13.19	0.08	...	....	750	1380	90,500	66,500	26	66	100	179
0.10	16.25	0.03	...	..	750	1380	72,000	42,000	30	56	60	137
0.10	17.28	0.031	...	....	750	1380	77,000	47,000	28	56	48	140
0.07	17.95	0.032		...	750	1380	72,000	44,700	29	60	42	140
0.07	16.39	0.12	...	....	750	1380	92,000	61,000	27	66	86	183
0.06	17.23	0.11	...	....	750	1380	94,500	63,000	27	61	62	179
0.08	18.46	0.17	.	....	750	1380	103,000	68,000	25	57	61	174

* Franks.(360)

per cent nitrogen.) Franks(360) showed that this effect is not accompanied by embrittlement, or by reduced resistance to corrosion. It was observed also that the nitrogen addition causes marked reduction of grain size. Some of the results are given in Table 23. It was concluded that to obtain the greatest strength and toughness, the low-carbon 10 to 14 per cent chromium steels should contain from 0.05 to 0.10 per cent nitrogen, and the 15 to 18 per cent chromium steels from 0.08 to 0.16 per cent nitrogen.

54. Effects of Columbium and Titanium.—In 1933, Becket and Franks(308) described the effects of columbium and titanium on low-carbon iron-chromium alloys. Columbium, in amounts 8 to 10 times the carbon content, and titanium, in amounts 5 to 7 times the carbon content, eliminate the martensitic structure of the 15 to 18 per cent chromium steels, leaving a structure of chromium ferrite and carbides. Thus, "carbon-neutralizing"

TABLE 24.—INFLUENCE OF COLUMBIUM AND TITANIUM ON THE LOW-CARBON 10 TO 18 PER CENT CHROMIUM STEELS*

Composition, per cent				Heat treatment	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
C	Cr	Cb	Ti						
0.10	12.42	1.18	....	As hot rolled	63,300	39,200	30	53	121
0.10	12.42	1.18	...	Air cooled after 4 hr. at 750°C. (1380°F.)	64,500	37,000	31	65	116
0.10	12.42	1.18	...	Air cooled after 10 min. at 900°C. (1650°F.)	63,000	39,000	37	73	112
0.11	13.35	...	0.85	As hot rolled	63,400	36,000	25	70	126
0.11	13.35	..	.	Air cooled after 4 hr. at 750°C. (1380°F.)	63,400	39,000	28	70	112
0.11	13.35	....	.	Air cooled after 10 min. at 900°C. (1650°F.)	64,000	36,000	33	75	112
0.13	18.65	...	0.78	As hot rolled	71,500	49,000	31	69	131
0.13	18.65	...	0.78	Air cooled after 4 hr. at 750°C. (1380°F.)	76,000	50,000	29	66	131
0.13	18.65	...	0.78	Air cooled after 10 min. at 900°C (1650°F.)	68,000	40,000	32	66	118
0.07	19.20	....	1.00	As hot rolled	72,000	52,000	22	41	149
0.07	19.20	...	1.00	Air cooled after 4 hr. at 750°C. (1380°F.)	69,500	43,000	31	65	137
0.07	19.20	....	1.00	Air cooled after 10 min. at 900°C. (1650°F.)	72,000	45,000	29	63	118

* Becket and Franks.(308)

additions soften the material; larger additions, of which the excess is dissolved in the ferrite, increase strength and hardness. Some of the experimental data are reproduced in Table 24. Later, Tofaute(477) determined the properties of annealed 16 to 18 per cent chromium steels with and without additions of such elements as titanium, tantalum, columbium, and molybdenum. Results of tests on sheet samples are given in Table 25. Tofaute concluded from these preliminary tests that the steels so modified had improved fabricating properties and were more resistant to corrosion.

TABLE 25.—MECHANICAL PROPERTIES OF ANNEALED LOW-CARBON IRON-CHROMIUM ALLOYS, WITH AND WITHOUT ADDITIONS OF MOLYBDENUM, TITANIUM, TANTALUM, OR COLUMBIUM. SPECIMENS PREPARED FROM 0.6-MM. (0.023-IN.) SHEET*

Mark	Composition, per cent					Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation, per cent $(l = 11.3\sqrt{A})$
	C	Si	Mn	Cr	Others			
1	0.10	0.35	0.47	16.5	....	72,700	48,400	24.2
2	0.11	0.85	0.49	17.9	1.24 Ti	79,700	51,200	23.4
3	0.13	0.39	0.42	17.4	2.10 Mo	73,300	45,500	23.7
4	0.04	0.44	0.36	18.2	.. . .	57,700	34,800	27.3
5	0.06	0.04	0.41	16.8	0.88 Ti	75,400	49,800	22.1
6	0.04	0.42	0.41	17.5	1.09 Ta, 0.09 Cb	67,300	35,600	23.6
7	0.05	0.55	0.55	18.4	0.09 Ta, 0.71 Cb	76,400	49,800	19.0
8	0.04	0.35	0.47	19.2	0.31 Ta, 0.35 Cb	67,300	43,400	17.0
9	0.05	0.30	0.27	17.4	2.08 Mo	78,500	54,000	24.1
10	0.05	1.83	0.52	18.1	....	87,600	66,100	14.2

* Tofaute.(477)

55. Effects of Other Additions.—*Silicon* in excess of the small percentages always present in low-carbon iron-chromium alloys is desirable in some instances. The effect of up to 3 per cent silicon in low-carbon 12 per cent chromium steels was described by Grossmann;(85) this element, like chromium, extends the delta region, although silicon is the more powerful. It favors the existence of ferrite, which means reduced air hardenability, increased grain size, and, consequently, reduced toughness in impact. The same effects are produced in the low-carbon 16 to 18 per cent chromium steels. *Aluminum* acts in much the same way as silicon. Monypenny(191) stated that 1 per cent aluminum prevented hardening in a low-carbon 12 per cent chromium steel which had low toughness and consisted of large grains. A steel of this type is being manufactured in the United States for applications requiring freedom from air hardening. It contains 0.08 per cent maximum carbon, 11.5 to 13.5 per cent chromium, and from 0.10 to 0.20 per cent aluminum; this steel, however, retains much of the toughness of the aluminum-free alloy.* The effects of large amounts of aluminum in special alloys are discussed in Chapter XVI.

Sulphur is used extensively in low-carbon 10 to 14 per cent chromium steels to promote free-machining and non-seizing characteristics. According to Palmer,(104) 0.12 per cent sulphur increases these properties, but 0.30 per cent is required for the best results; hot workability, however, is seriously affected by more than 0.20 per cent sulphur. This difficulty has been overcome by having zirconium together with sulphur present in the steel. Mochel(74) claimed that the sulphur addition results in transverse weakness although the longitudinal properties are only slightly affected. Palmer(104) also investigated the effect of up to 0.50 per cent *phosphorus;* the hot-working properties of the steels were not seriously affected, but he found no advantage in its use.

56. Carburizing and Nitriding.—Inasmuch as the low-carbon 10 to 18 per cent chromium steels are used primarily because of their resistance to corrosion, it is not strange that there is but little information on the carburizing and nitriding of them, especially as, in general, these operations decrease the corrosion resistance. For completeness, however, brief reference may be made to the study of Widawski(480) on carburizing and of Jones(325) on nitriding. The former heated an alloy containing 0.12 per cent carbon and 13.9 per cent chromium in carburizing mixtures at several temperatures for varying lengths of time. Carbon was absorbed readily at temperatures of 900°C. (1650°F.) and higher, to form hard cases. Jones experimented with an alloy containing 0.14 per cent carbon, 1.7 per cent nickel, and 17.8 per cent chromium. A surface hardness greater than 900 Vickers resulted from nitriding at temperatures ranging from 500 to 640°C. (930 to 1185°F.). Increased temperature increased the depth of case without much loss of hardness. Two-stage nitriding, consisting of 24 hr. at 500 to 510°C. (930 to 950°F.), then 24 hr. at 600 to 610°C. (1110 to 1130°F.), produced a surface of 1150 Vickers and a depth of case of 0.01 in. Uniform hardening by this method seems to demand a surface relatively free from oxide.

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* V. B. Browne, private communication.

C. PHYSICAL CONSTANTS

It is the purpose of this portion of the chapter to review the data on such quantities as lattice constants, thermal expansion, thermal conductivity, electric resistivity, and magnetic properties of the low-carbon 10 to 18 per cent chromium steels.

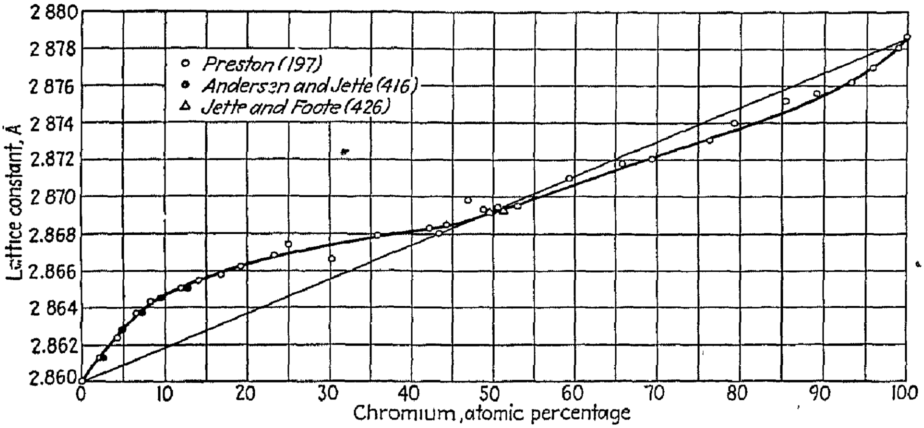

FIG. 19.—Lattice constants of iron-chromium alloys at 20°C.

57. Lattice Constants and Specific Volume.—The course of the lattice-constant curve for steels cooled too rapidly to permit separation of the sigma phase has been established with considerable certainty by the data obtained by Preston,(197) Andersen and Jette,(416) and Jette and Foote.(426) Results of the several investigations are in excellent agreement, as may be seen by inspection of Fig. 19. The curve is unusual in that both positive and negative deviations from rule-of-mixtures values exist; this behavior is perhaps ascribable to the tendency to form the sigma phase. Values of specific volume, measured by Adcock(168) and by Stäblein,(130) are given in Fig. 20. They are plotted against weight percentage because it is a thermodynamic deduction that the specific volume (not density) of an ideal solution is a linear function of weight percentage. The deviation of the measured values is seen to be similar to that of the lattice constants.

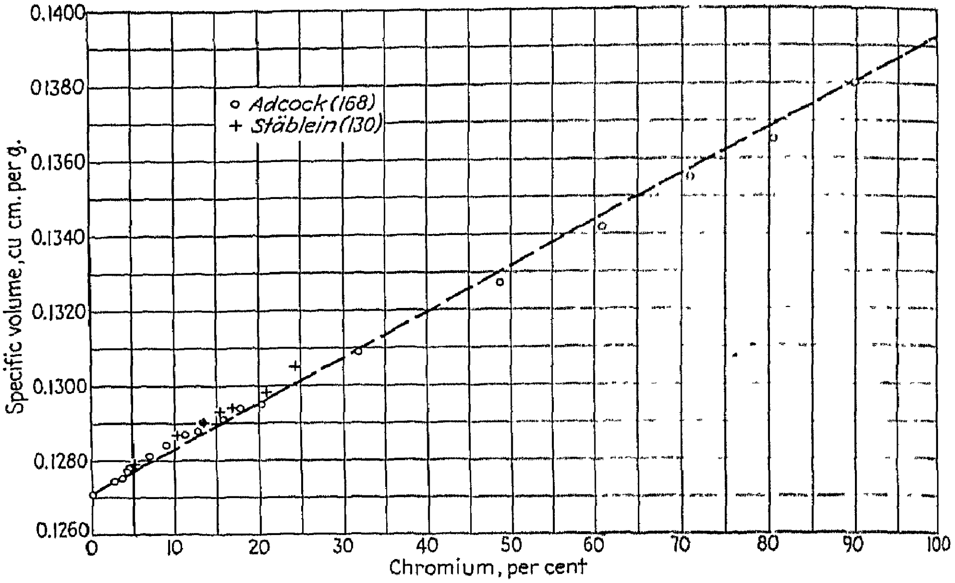

FIG. 20.—Specific volume of iron-chromium alloys at 20°C.

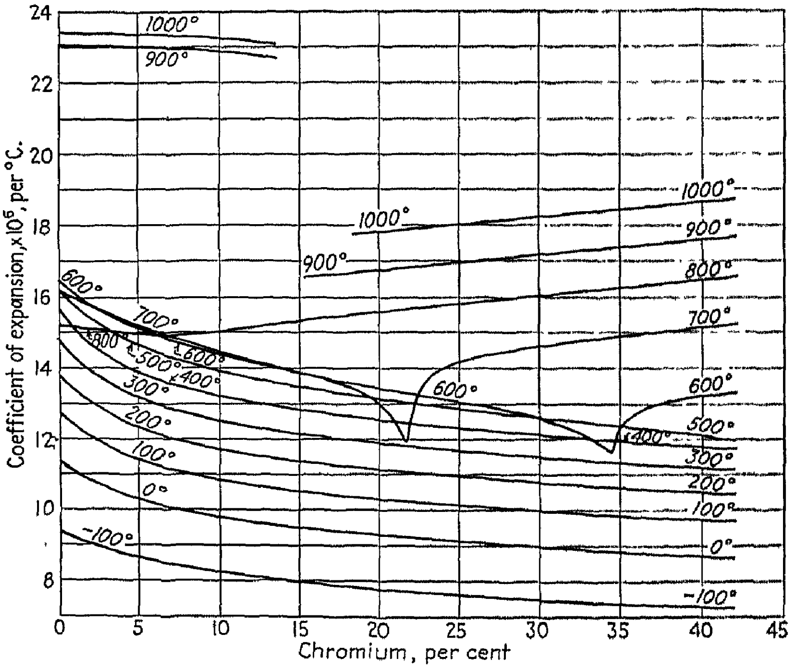

FIG. 21.—Coefficients of thermal expansion of iron-chromium alloys. (*Chevenard*.(81))

According to Benedicks, Ericsson, and Ericson,(109) the specific volume of a 13.7 per cent chromium alloy is 0.1387 cu. cm. per g. at the temperature of melting, and 0.1420 cu. cm. per g. at 1600°C. (2910°F.).

58. Thermal Expansion.—The first small additions of chromium to iron cause a relatively large reduction of the coefficient of expansion, as is shown clearly by the curves of Fig. 21, given by Chevenard.(81) The effect is much less pronounced with substantial percentages of chromium in the temperature range in which the alloys are ferromagnetic. The coefficient of non-ferromagnetic alloys appears to be increased regularly with increased chromium concentration. According to the slope of the two curves for gamma-phase alloys, shown in the upper left portion of Fig. 21, the coefficient is decreased slightly by increased chromium concentration. Other data are in agreement with the indications of Chevenard's curves; Ruf,(105) for example, found for the 0 to 250°C. (32 to 480°F.) range a decrease of mean coefficient from 12.6×10^{-6} for iron to 9.3×10^{-6} at 50 per cent chromium.

Data on a series of alloys containing about 0.12 per cent carbon were given recently by Jones and Heselwood(498); they are reproduced in Table 26. These and earlier measurements of Hidnert and Sweeney(88) on alloys containing 0.09 to 0.13 per cent carbon and 12 to 16 per cent chromium also show that the coeffi-

TABLE 26.—THE MEAN COEFFICIENT OF EXPANSION OF SOME IRON-CHROMIUM ALLOYS CONTAINING 0.12 PER CENT CARBON*

Temperature		Mean coefficient of expansion $\times 10^6$, for a chromium content of			
°C.	°F.	11.96 per cent	17.48 per cent	24.53 per cent	32.27 per cent
20 to 200	70 to 390	11.15	10.70	10.40	10.20
20 to 300	70 to 570	11.45	11.00	10.70	10.50
20 to 400	70 to 750	11.70	11.30	11.00	10.80
20 to 500	70 to 930	12.00	11.55	11.30	11.00
20 to 600	70 to 1110	12.30	11.80	11.50	11.10
20 to 700	70 to 1290	12.55	12.05	11.70	11.40

* Jones and Heselwood.(498)

cients of these industrially important alloys are somewhat smaller than those of alpha iron but not very different from them.

59. Thermal Conductivity.—The most reliable data on thermal conductivity were obtained by Shelton and Swanger(204) and by Maurer.(432) Data obtained by the former on four high-chromium alloys are given in Table 27. In general, the thermal conductivity of pure metals and low-alloy steels decreased with increase of temperature, whereas the reverse was true of high-alloy materials. That the iron-chromium alloys were no exception may be seen by inspection of Fig. 22. Both curves indicate that the U-shaped curve found so often for solid solutions exists also for this system. A few data on low-carbon alloys obtained by Maurer are in fair agreement with those of Shelton and Swanger. Other data indicate no change of conductivity from 30 to 1100°C. (85 to 2010°F.) for a 0.07 per cent carbon, 13.08 per cent chromium alloy. Similar behavior was found for a 20.63 per cent chromium alloy (of the same carbon content) up to 400°C. (750°F.), but as 1000°C. (1830°F.) was approached, conductivity increased more and more rapidly from 0.234 to 0.293 watt per cm. per °C.

TABLE 27.—THE THERMAL CONDUCTIVITY OF SOME ANNEALED IRON-CHROMIUM ALLOYS*

Mark	Composition, per cent							Thermal conductivity, watts per cm. per °C.,† at				
	C	Cr	Ni	Mn	Si	S	P	100°C.	200°C.	300°C.	400°C.	500°C.
A_1	0.08	15.19	0.05	0.35	0.20	0.017	0.020	0.261	0.262	0.262	0.262	0.262
A_2	0.07	12.00	0.23	0.09	0.09	0.010	0.015	0.249	0.250	0.268	0.277	
A_3	0.14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.243	0.247	0.252	0.256	0.261
A_4	0.10	26.00	0.18	0.40	0.45	0.008	0.013	0.209	0.210	0.220	0.238	0.243

* Shelton and Swanger.(204)

† 1 watt per cm. per °C. = 0.239 cal. per sec. per sq. cm. (°C. per cm.).

60. Electric Properties.—The more extensive data on the electric resistivity of iron-chromium alloys at 20°C. (70°F.) are collected in Fig. 23. On the basis of care exercised in preparation of specimens, the data of Adcock(168) should be most reliable, and this seems to be substantiated because, for a given chromium content, the values of Ruf,(105) Stäblein,(130) and Fischer(135) for less pure alloys are invariably greater. The erratic readings by Adcock for alloys containing approximately 70 and 80 per cent chromium indicate the need of further work, at least in this region, although the practical significance of this portion of the resistivity curve is doubtful. The curve as drawn merely indicates probable values for alloys of purity comparable to that of Adcock's specimens. The resistivity of industrial alloys may be expected to be greater, perhaps by amounts indicated by the points of Ruf and of Fischer. Ruf's resistivity curves for higher temperatures are shown in Fig. 24.

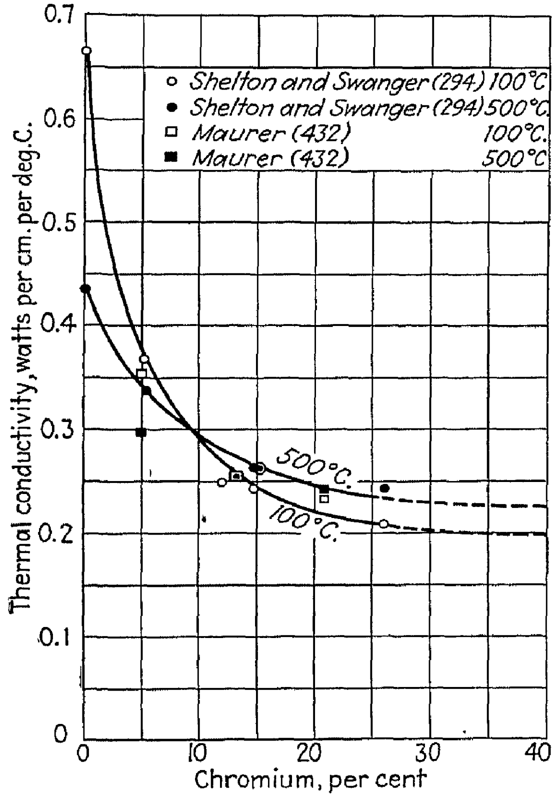

FIG. 22.—Thermal conductivity of iron-chromium alloys.

Data given by Fuller⁽¹⁰⁾ on the thermal electromotive force of five alloys containing up to 29.4 per cent chromium, in comparison with copper, at temperatures between 0 and 100°C. (32 and 210°F.), indicate reduction of value with increasing chromium content. More detailed results for alloys containing up to 50 per cent chromium, in comparison with platinum, were given by Ruf;(105) temperatures ranged to 1000°C. Similar data for a 25 per cent chromium alloy were given by Ballay;(171) but they differ in magnitude.

61. Magnetic Properties.—Data that appear to be the most reliable on the magnetization of iron-chromium alloys at room temperature are collected in Fig. 25. Those on intrinsic (or ferric) induction, which are numerically equal to 4π times saturation intensity of magnetization, obtained by Stäblein(130) and by Ebert and Kussmann,(452) indicate the possibility of a linear variation with atomic percentage, and the further possibility that the line for absolute zero declines to zero intrinsic induction at 75 atomic per cent chromium. The disappearance of ferromagnetism at simple ratios of atoms has been observed in other alloy systems. Other curves show magnetic induction for field strengths of 1 and 100 oersteds, based on data reported by Adcock.(168) The variation in the points of the smaller field strength is not unusual.

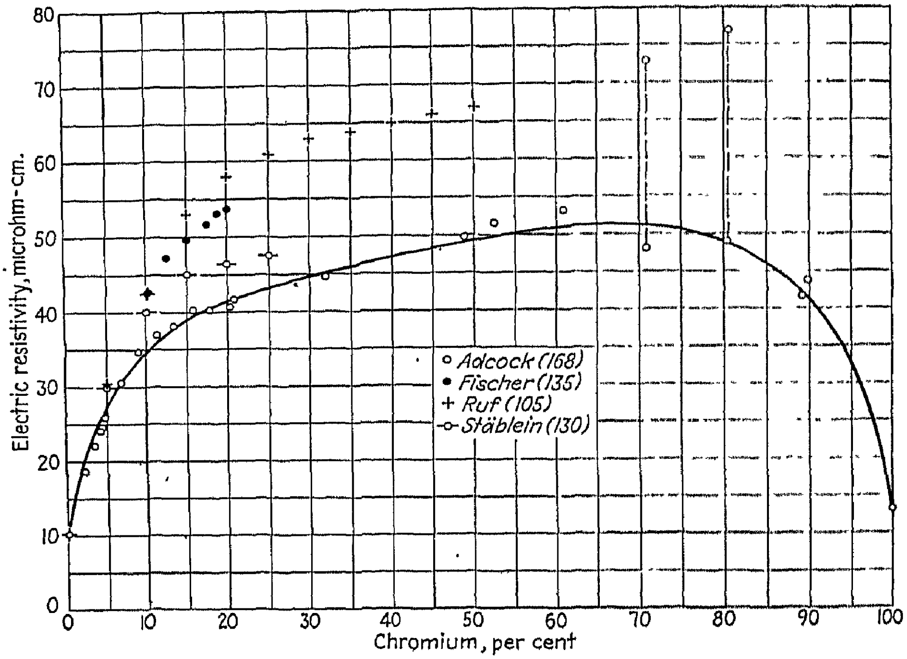

FIG. 23.—Electric resistivity of iron-chromium alloys.

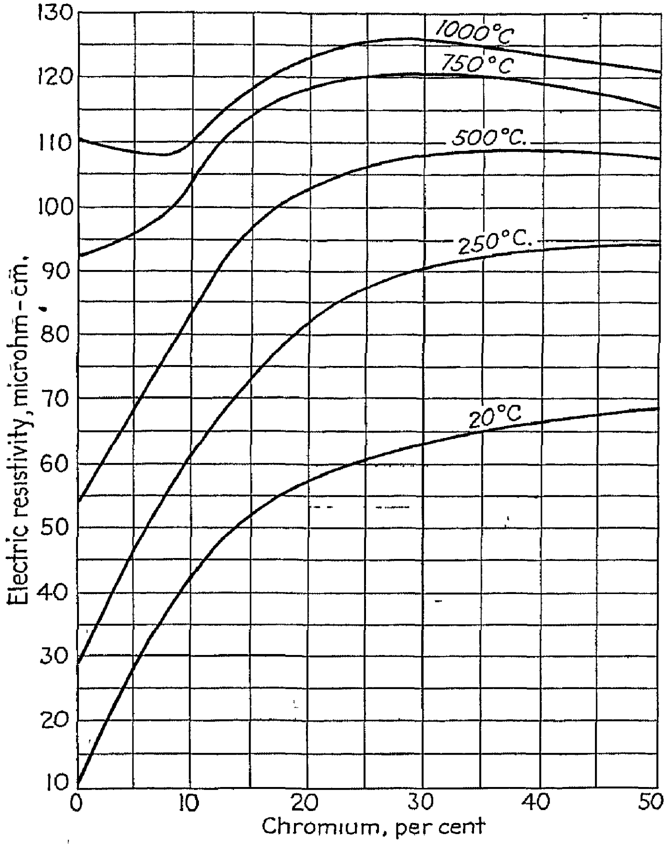

FIG. 24.—The effect of temperature on the electric resistivity of iron-chromium alloys. (*Ruf.*(105))

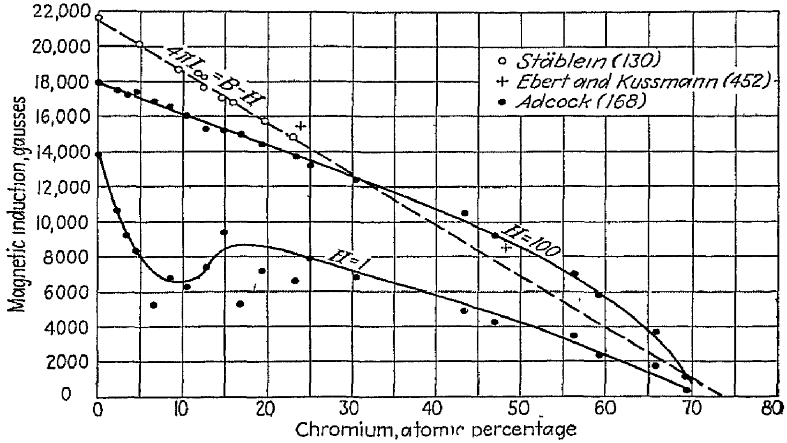

FIG. 25.—Magnetic induction of iron-chromium alloys.

Data on alloys containing 10 to 20 per cent chromium, less pure than those of Adcock, probably comparable with industrial alloys, were given by Fischer;(135) these are summarized in Table 28. The best results, from the standpoint of highest permeability and lowest hysteresis loss, were obtained with annealed specimens containing 17.5 and 18.7 per cent chromium; this was ascribed to minimum magnetostriction. The properties listed in Table 28 are seen to be inferior to those of materials ordinarily used in magnetic circuits, but they may be of interest for possible applications requiring high resistance to certain forms of corrosion.

TABLE 28.—SUMMARY OF MAGNETIC PROPERTIES OF IRON-CHROMIUM ALLOYS VACUUM ANNEALED AT 1000°C. (1830°F.)*

Chromium, per cent	Maximum permeability	Induction for maximum permeability, gausses	Coercive force, oersteds, for maximum induction of		Residual induction, gausses, for maximum induction of		Hysteresis loss, ergs per cu. cm. per cycle, for maximum induction of	
			10,000 gausses	5000 gausses	10,000 gausses	5000 gausses	10,000 gausses	5000 gausses
10	620	7000	5.90	4.30	6450	3100	15,600	5090
12.5	676	5880	4.50	2.95	5400	2780	11,900	3510
15	974	6260	3.80	2.85	7350	3370	10,800	3440
17.5	1660	5360	2.25	1.40	7700	3040	6,900	1840
18.7	1890	5500	2.00	1.40	7350	3080	6,200	1770
20	975	7300	5.00	3.54	8300	3410	13,700	4090

* Fischer.(135)

A few other scattered data do not seem to add anything of interest. On the whole, the purer the alloys the greater the permeability at a given induction, the smaller the coercive force, and the smaller the hysteresis loss. Since there are magnetic materials far better than iron-chromium alloys, the latter are unlikely to find industrial application.

D. CORROSION

Of the common elements alloyed with iron, chromium is of the greatest utility in the production of a variety of alloys having marked resistance to corrosion. Iron-chromium alloys cóntaining at least 12 per cent chromium have useful resistance to rusting. Resistance to a broader range of conditions is greater when the chromium content is increased to 20 per cent, but mechanical properties and workability, as well as cost, undergo change with the increased chromium concentration; consequently, there are factors other than those of corrosion behavior to consider for a given application.

The outstanding characteristic of high-chromium steels is their ability to become passive under suitable conditions, and suitable conditions include exposure to a medium having sufficient oxidizing power to form and maintain a stable oxide film. The passive state means that the rate of corrosion under oxidizing conditions is reduced to small value, and not that attack is prevented altogether.

Of the many factors to be considered in interpreting corrosion behavior, the most important for the steels under discussion is chromium content; in general, the greater the chromium content, the wider the range of conditions under which the passive state can be produced. Carbon content is important also, especially if this element is present in amount in excess of the solubility limit, as it is in nearly all industrial steels. The precipitation of carbide reduces the resistance to corrosion of the alloy. Thus, maximum resistance requires that carbide precipitation be suppressed by heat treatment, if it is not feasible to produce an alloy of carbon content within the solubility limit.

Generalizations on corrosion behavior of course apply to all materials. It is therefore difficult to single out low-carbon iron-chromium alloys, and it is suggested that the data given here be examined in comparison with those on other materials, including modified iron-chromium alloys discussed elsewhere in this volume.

62. Corrosion by Nitric Acid.—Iron-chromium alloys are used widely for the handling of nitric acid. Corrosion rates of 10 mg. per sq. dm. per day or less are common, according to McKay and Worthington.(431) Corrosion is usually greater in the more dilute acid concentrations—less than 20 per cent nitric acid—but it has been found that even these are resisted satisfactorily by alloys containing at least 18 per cent chromium. Some actual data are collected in Fig. 26. Rates shown by data of Pilling and Ackerman(123) are higher than those found under service conditions; this has been ascribed to the fact that the specimens were given a treatment before testing that was not conducive to the greatest resistance of which iron-chromium alloys are capable. Tests were made in aerated, agitated 5 and 35 per cent acid solutions at 30°C. (85°F.). Other curves shown were constructed from data of MacQuigg[(78)] and of Huey.[(144)]

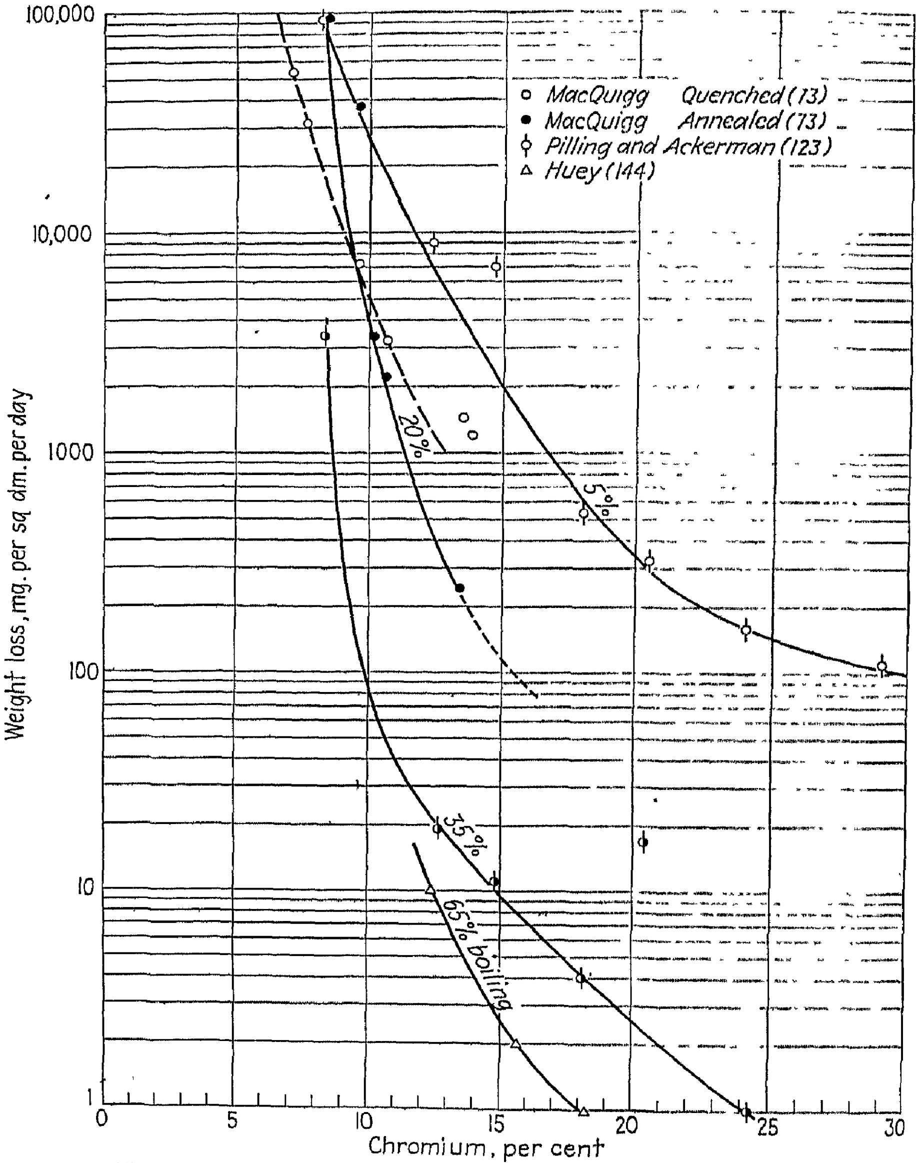

FIG. 26.—Corrosion of iron-chromium alloys by nitric acid.

Steels containing 12 to 14 per cent chromium are usually corroded by boiling acid in the 1 to 20 per cent range, but those

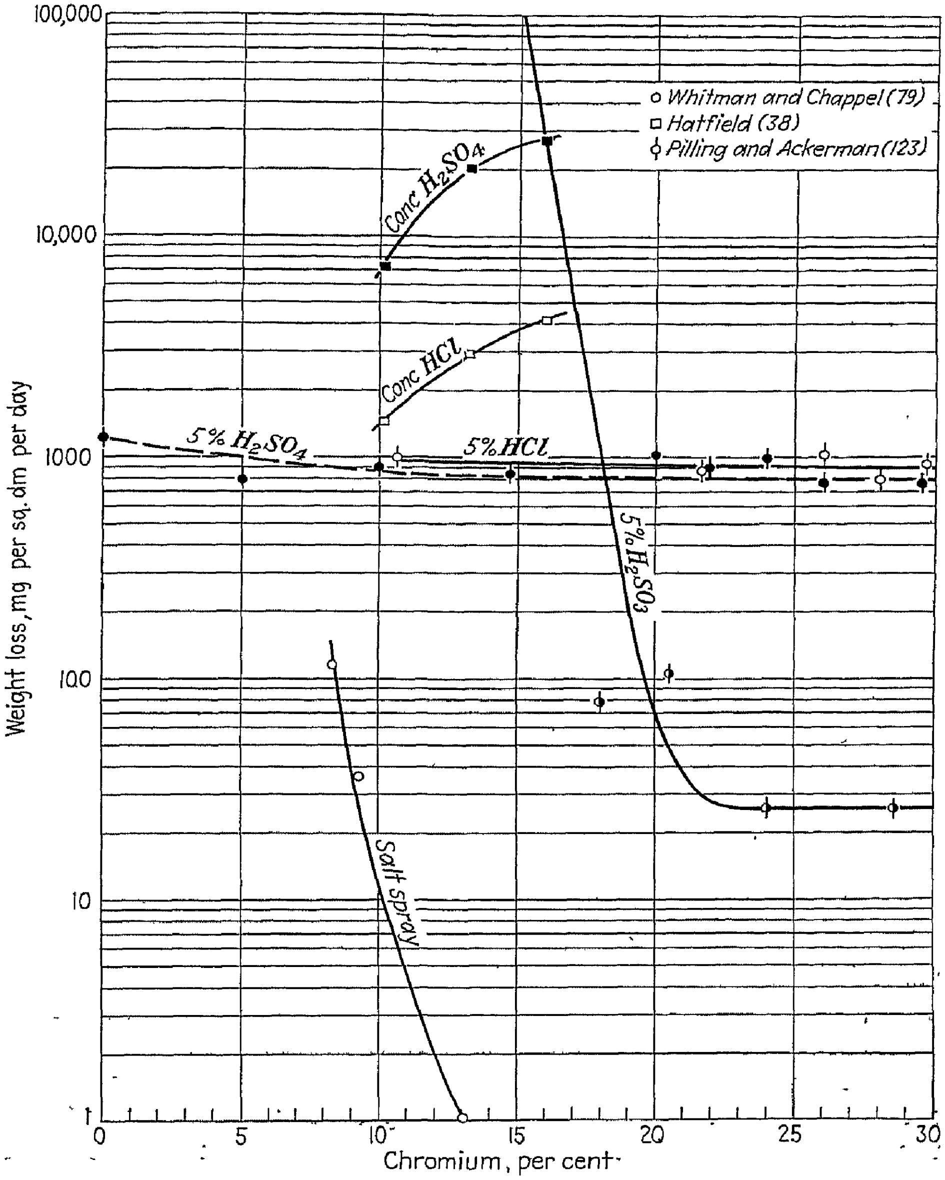

FIG. 27.—Corrosion of iron-chromium alloys by various media.

of greater chromium content are likely to resist acid attack at both the boiling point and room temperature. A usual concentration of nitric acid made from atmospheric nitrogen is 55 to 65 per cent; the curve for 65 per cent boiling acid shows that iron-chromium alloys are suitable for this class of service.

The usual precautions in interpreting corrosion data apply especially if the acid contains chloride or other halide ions, because they are very effective at destroying passivity. Such impurity is likely to be present in acid made from sodium nitrate.

63. Corrosion by Other Media.—Data on the corrosion of iron-chromium alloys by hydrochloric, sulphuric, and sulphurous acids, obtained by Hatfield(38) and by Pilling and Ackerman,(123) are collected in Fig. 27. In general, these materials are attacked readily by hydrochloric acid, although passivity has been induced in isolated instances, according to McKay and Worthington.(431) Alloys containing substantial percentages of nickel and molybdenum in addition to chromium, discussed elsewhere, seem to be most promising in resisting this acid.

Sulphuric acid is usually corrosive to high-chromium steels unless the solution has sufficient oxidizing power to establish passivity. Pilling and Ackerman's data for corrosion by aerated, agitated 5 per cent acid show no evidence of passivity in the 0 to 30 per cent chromium range. Data from the same source on corrosion by sulphurous acid indicate that passivity is well developed in alloys containing at least 20 per cent chromium, however.

The curve for salt-spray corrosion, drawn from data of Whitman and Chappell,(79) indicates that the 12 to 14 per cent chromium alloys have considerable resistance to attack by this medium.

Semiquantitative data on the resistance of iron-chromium alloys to a variety of substances, as reported by a manufacturer,(506) are given in Table 29. The high resistance to most organic acids indicated is confirmed by the fact that chromium steels are well known to be passive to exposure to food products.

64. Atmospheric Corrosion.—Certain of the chromium steels are capable of resisting change of appearance upon exposure to the atmosphere. The low-carbon 11 to 14 per cent chromium steels rust, but the rusting is not progressive. According to McKay and Worthington,(431) the 18 per cent chromium steels retain a large proportion of their brightness after prolonged exposure to average urban and rural atmospheres, are slightly

TABLE 29.—THE RESISTANCE TO VARIOUS MEDIA OF LOW-CARBON ALLOYS CONTAINING 10 TO 18 PER CENT CHROMIUM*

Medium	Concentration, per cent	Temperature	Resistance†	
			14 to 18 %Cr	10 to 13.5 %Cr
		Acids		
Acetic	5	Room	C	S
	20	Room	S	H
	100	Room	H	H
Acetic anhydride	....	Room	H	H
Benzoic	5	Boiling	C	C
Boric	5	Boiling	C	C
Butyric	5	Boiling	C	C
Carbolic	5	Boiling	C	C
Citric	5	Room	S	S
Citric	25	Boiling	H	H
Chromic, c.p.	10	Room	S	S
Formic	5	Room	H	H
Gallic	5	Room	C	C
Hydrochloric	All	....	H	H
Hydrofluoric	All	....	H	H
Lactic	5	Room	H	H
Malic	5	Room	C	C
Nitric	5	Room	C	S
Nitric	50	Room	C	C
	65	Boiling	S	H
Oleic	Concentrated	95°C. (200°F.)	C	C
Oxalic	5	Room	S	H
Phosphoric	5	Room	S	S
Stearic	Concentrated	95°C (200°F.)	C	C
Sulphuric	Dilute	Room	H	H
	Concentrated	Room	C	C
Sulphuric plus sulphates	Many	....	C	C
Sulphuric plus nitrates	Many	....	C	C
Sulphurous	Saturated	Room	S	H
Tannic	10	Room	C	C
Tartaric	10	Room	H	H
		Salts and bases		
Aluminum sulphate	10	Room	H	H
chloride	5	Room	H	H
fluoride	5	Room	H	H

TABLE 29.—THE RESISTANCE TO VARIOUS MEDIA OF LOW-CARBON ALLOYS CONTAINING 10 TO 18 PER CENT CHROMIUM.*—(*Continued*)

Medium	Concentration, per cent	Temperature	Resistance†	
			14 to 18 %Cr	10 to 13.5 %Cr
Salts and bases—(*Continued*)				
Ammonium hydroxide	All	Room	C	C
bromide	5	Room	S	S
chloride	5	Room	S	S
carbonate	All	Any	C	C
nitrate	5	Room	C	C
oxalate	5	Room	C	C
phosphate	5	Room	C	C
sulphate	10	Room	S	S
sulphate	10	Boiling	S	H
Barium chloride	5	Room	C	S
Calcium chloride	5	Room	S	S
hypochlorite	3	Room	H	H
hydroxide	5	Room	C	C
Copper chloride	1	Room	H	H
cyanide	Plating solution	....	C	C
cyanide	5	Room	C	C
sulphate	10	Room	C	C
Ferric chloride	5	Room	H	H
nitrate	5	Room	C	C
sulphate	5	Room	C	C
Ferrous sulphate	5	Room	C	C
Magnesium chloride	5	Room	S	S
hydroxide	Thick suspensions	Room	C	C
Mercuric chloride	Dilute	Room	H	H
Potassium dichromate	5	Boiling	C	C
bromide	5	Room	S	S
carbonate	All	Room	C	C
chloride	5	Room	S	S
hydroxide	5	Room	C	C
nitrate	5	Room	C	C
sulphate	5	Room	C	C
Sodium acetate	5	Room	C	C
carbonate	All	Room	C	C
chloride	5	Room	S	S
bromide	5	Room	S	S
fluoride	5	Room	S	S
hydroxide	10	Room	C	C

TABLE 29.—THE RESISTANCE TO VARIOUS MEDIA OF LOW-CARBON ALLOYS CONTAINING 10 TO 18 PER CENT CHROMIUM.*—(*Continued*)

Medium	Concentration, per cent	Temperature	Resistance†	
			14 to 18 %Cr	10 to 13.5 %Cr
Salts and bases—(*Continued*)				
Sodium hypochlorite	5	Room	H	H
nitrate	All	Room	C	C
phosphate	5	Room	C	C
sulphate	5	Room	C	C
sulphate	Concentrated	Room	H	H
sulphide	Concentrated	Room	C	C
sulphite	5	Room	S	S
Stannous chloride	5	Room	H	H
Stannic chloride	5	Room	H	H
Zinc chloride	5	Room	S	H
	5	Boiling	H	H
sulphate	5	Room	C	C
Miscellaneous				
Alcohol, ethyl and methyl	...	Room	C	C
Aniline	...	Room	C	C
Beer	...	Room	C	C
Benzene	...	Room	C	C
Buttermilk and milk	...	...	C	C
Coffee	...	Boiling	C	C
Cider	...	...	C	C
Ether	...	...	C	C
Food products	...	...	C	C
Formaldehyde	...	...	C	C
Fruit juices	...	...	C	C
Linseed oil	...	Hot	C	S
Meats	...	...	C	C
Vegetable juices	...	Hot	C	C
Vinegar	...	...	C	C
Vinegar and salt	...	Hot	C	S
Wet coal or cinders	...	...	C	C

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* Rustless Iron and Steel Corporation.(506)

† C = resistance ordinarily complete. S = slight attack, suitable for some uses. H = high rate of attack.

stained in mild industrial atmospheres, and are likely to become pitted in strongly sulphurous industrial and in marine atmospheres.

65. Oxidation Resistance.—The most useful non-precious metals for resisting high temperatures are chromium-nickel, iron-chromium-nickel, and iron-chromium alloys. Their suitability arises from the fact that they form adherent oxide coatings. Ordinary steel is subject to marked scaling at temperatures ranging upward from about 540°C. (1000°F.). Steels containing 11 to 14 per cent chromium are resistant at temperatures up to about 815°C. (1500°F.). Increase of chromium content to 16 to 18 per cent increases the range of suitability to 870°C. (1600°F.). This is in agreement with recent findings of Preece, Richardson, Simister, and Cobb(526) whose test materials included low-carbon steels containing about 13 and about 17 per cent chromium. Resistance to scaling in various atmospheres was dependent upon chromium content and upon the nature of the atmosphere. Scaling followed the breakdown of a surface film consisting chiefly of chromium oxide formed in the initial period; this resulted in uncertainty of the quantitative results. Data on the scaling of some alloys by pure oxygen, obtained by Hatfield,(86) are given in Table 30. Further increased chromium content is sometimes useful; for example, Heindlhofer and Larsen(275) found the scaling rate at 27 per cent chromium to be about one one-hundredth of that of iron at 1100°C. (2010°F.).

Chromium is the necessary element for providing resistance to sulphur dioxide at elevated temperatures. According to McKay

TABLE 30.—THE CORROSION OF SOME CHROMIUM ALLOYS BY OXYGEN*

Composition, per cent		Weight gain, mg. per sq. cm. per day, at			
Cr	Ni	700°C. (1290°F.)	800°C. (1470°F.)	900°C. (1650°F.)	1000°C. (1830°F.)
13 1	..	67	570	840	27,500
18.5		180	220	570	870
17 7	8	320	315	820	1,700
12	60	72	148	230	530

* Hatfield.(86)

and Worthington,(431) iron-chromium alloys containing about 30 per cent chromium are best. More complete data on alloys for high-temperature service are given elsewhere in this volume.

E. CASTINGS

The low-carbon iron-chromium alloys are often used in the cast form. The literature is not voluminous, and the brief discussion here is drawn from the descriptions of Strauss,(248) Jones,(374,375) the "Cast Metals Handbook,"(343) and Lemoine.(379) According to Jones, castings containing a maximum of 0.15 per cent carbon and 10 to 14 per cent chromium have been produced in "fairly large quantities." This is true also of the 16 to 20 per cent chromium grades.

If the carbon content is restricted to a maximum of 0.12 per cent, difficulty arises in the casting of thin sections. Satisfactory fluidity is obtained by superheating the metal; this practice is conducive to large grains, and special care is required to overcome the additional problems in shrinkage and porosity.

66. Castings Containing 10 to 14 Per Cent Chromium.—Compositions normally used for wrought alloys containing 10 to 14 per cent chromium are used for cast products. According to Jones,(374) nickel can be added up to 1 per cent to increase tensile and yield strengths without concomitant great loss of ductility. These compositions are somewhat responsive to heat treatment. For best results they are either quenched or normalized at not less than 1010°C. (1850°F.). Their resistance to corrosion is about the same as that of the wrought materials of the same composition. Applications of such castings are pump and valve parts and gears that must withstand mild corrosion. A free-machining grade is produced by adding 0.25 to 0.40 per cent sulphur.

Typical compositions and properties, selected from those given by Strauss(248) and Jones,(374) are subjoined:

Element, percentage:	
Carbon	0.08 to 0.12
Chromium	11.5 to 14.0
Nickel	0 25 to 1.0
Silicon	0.5 to 1.0
Manganese	0.3 to 0.6
Sulphur	Less than 0.05
Phosphorus	Less than 0.05

Properties:

Tensile strength, lb. per sq. in.	75,000 to 100,000
Yield strength, lb. per sq. in.	45,000 to 65,000
Elongation in 2 in., per cent.	18 to 25
Reduction of area, per cent.	30 to 50
Brinell hardness.	150 to 200

Density ranges from 7.6 to 7.8 g. per cu. cm. In machining, the behavior is about the same as that of medium-carbon steel.

67. Castings Containing 16 to 20 Per Cent Chromium.—According to Jones,(374) it is difficult to make low-carbon castings containing 16 to 20 per cent chromium, especially if they are thin-walled, because it is necessary to increase the pouring temperature to such a point that a coarse, brittle structure is inevitable. This is illustrated by the data of Table 31. Remedies are pouring at the lowest possible temperature and careful design. Another is to increase the carbon content to 0.2 to 0.3 per cent; this improves castability but impairs resistance to corrosion; consequently, the chromium content is maintained at about the upper limit (20 per cent) for this grade of alloys. Copper is sometimes used as well to counteract the effect of the higher carbon content.

TABLE 31.—THE EFFECT OF POURING TEMPERATURE ON THE MECHANICAL PROPERTIES OF A CAST STEEL CONTAINING 0.2 PER CENT CARBON AND 18 PER CENT CHROMIUM*

Property	Poured hot	Poured at a temperature 45°C. (85°F.) lower
Tensile strength, lb. per sq. in.	64,700	88,000
Yield strength, lb. per sq. in.	49,500	51,500
Elongation in 2 in., per cent	3.1	6.3
Reduction of area, per cent	2.7	6.2

* Jones (374)

Properties summarized by Strauss(248) and Jones(374) indicate that strength increases and ductility decreases somewhat as the carbon content is increased from 0.1 per cent. Those subjoined are for the standard composition of 0.2 to 0.3 per cent carbon, 16 to 20 per cent chromium, and a maximum of 1 per cent nickel.

Tensile strength, lb. per sq. in.	80,000 to 105,000
Yield strength, lb. per sq. in.	55,000 to 75,000
Elongation in 2 in., per cent	5 to 12
Reduction of area, per cent	6 to 15
Brinell hardness	180 to 220
Density, g. per cu. cm	7.6
Shrinkage allowance	3/16 in. per ft.
Pouring temperature	1510 to 1595°C. (2750 to 2900°F.)

Thus, these alloys are less ductile than those of the 10 to 14 per cent chromium grade, but this is no drawback in many applications for which resistance to corrosion is most important. Their machinability—according to Strauss—is about the same as that of medium-carbon steel, and—according to Jones—is "comparable to that of a low-alloy structural cast steel of about the same Brinell hardness." Heat treatment consists of simple annealing by soaking at 815 to 845°C. (1500 to 1550°F.) about 1.5 times longer than for similar castings of carbon steel, furnace cooling to about 595°C. (1100°F.), and then air cooling.

The resistance to corrosion of the 16 to 20 per cent chromium steels is greater than that of steels containing 10 to 14 per cent chromium. According to Jones, castings are used for valve bodies, for handling equipment for nitric acid, and for trim for steam and oil equipment. The alloys acquire better resistance to elevated temperatures upon addition of copper; such castings are used, for example, for exhaust manifolds.

F. WELDING

Welding has become an important method of fabrication, and its use for certain stainless-steel equipment has become a practical necessity. Although the low-carbon 10 to 18 per cent chromium steels can be welded, it is necessary to employ special precautions to secure sound, clean welds having optimum properties. The oxyacetylene and the electric-arc processes are in common use, although the atomic-hydrogen process is favored by some.*

The technique of welding by the oxyacetylene process has been described by Miller,(190) who also enumerated the necessary precautions. The torch flame should be just large enough to ensure proper fusion, because too much heat causes the molten metal to boil (a porous weld is the result); the flame should be neutral, because excess acetylene causes carbon absorption in the weld metal (lowered corrosion resistance results); and the flame should not contain excess oxygen, since, otherwise, infusible oxide is formed (entrapped oxide results in weld metal of low quality).

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* G. R. Brophy, private communication.

Miller also recommended the use of a backing strip, especially when thin sections are welded, and flux applied along the line of the weld, on both the top and bottom surfaces, to prevent oxidation of the metal during welding. Without a suitable flux, it is practically impossible to obtain complete fusion at the bottom of the weld. This should be done in welding both light and heavy plate, and the welding should be carried to completion as rapidly as possible without puddling and should be done on only one side. If welding is required on both sides, the article should be preheated before welding the second side.

Since the low-carbon 10 to 14 per cent chromium steels are air hardening, the welds should be annealed at 650 to 750°C. (1200 to 1380°F.) to overcome brittleness. In Miller's opinion, the welding blowpipe might be used to anneal welds successfully when suitable furnaces are not available, although furnace annealing is preferable.

The same precautions were suggested for welding the low-carbon 15 to 18 per cent chromium steels. Although these steels are not so subject to air hardening as those of lower chromium content, they develop large grains both in the weld and in adjacent zones, which causes the metal to become relatively brittle. Annealing at 650 to 750°C. (1200 to 1380°F.) followed by air cooling is suggested. Some of Miller's data for 0.05-in. sheet of 15 to 18 per cent chromium steel are subjoined:

Property	Sheet as received	Welded and furnace annealed
Tensile strength, lb. per sq. in.	77,100	73,800
Yield strength, lb. per sq. in.	63,500	50,800
Elongation in 2 in., per cent	31.0	11.6

The electric-arc method was described by Hodge.(367) The metal arc is preferred in order to provide close control of the carbon content of the deposited metal, and, in general, the procedure is that followed for high-grade welding of carbon steels. The electrodes are smaller than those used for welding carbon steels of comparable thickness; further, the welding should be done with an electrode of the required composition coated with a flux to protect the deposited metal from air to ensure metal free of blowholes. The coatings contain such metals as ferromanganese, ferrotitanium, or aluminum, and compounds such as calcium carbonate, calcium fluoride, and silica.

For welding the low-carbon 10 to 18 per cent chromium steels, with electrodes of the same composition, Hodge suggested a welding current slightly less than that for carbon-steel electrodes of equivalent diameter. Since the characteristics of the arc vary with the type of coating, the proper current is best found by experiment. Direct-current welding is used in preference to alternating current, and reversed polarity (work negative) is preferred. Because of the air hardenability of the low-carbon 10 to 14 per cent chromium alloys, successful metal-arc welding demands preheating and annealing immediately after the work is finished. Hodge suggested that the field of application for these alloys might be extended in structures requiring moderate corrosion resistance if the carbon content of the metal could be lowered to 0.04 or 0.05 per cent, thus reducing air hardening, but this is not upheld by the available data.*

So far as the higher chromium alloys are concerned, Hodge recommended preheating to about 95°C. (200°F.). The welds are brittle unless annealed, but even so, such materials are less resistant to impact than the lower chromium grades. As shown on page 78, this is probably an unavoidable effect of increased chromium content. Thus, selection of a material for a given service, such as the chemical industry, is likely to require delicate balance between strength and resistance to corrosion.

Because of the recent publication by Spraragen and Claussen(527) of a comprehensive review of the literature on welding chromium and chromium-nickel corrosion- and heat-resisting steels, including the low-carbon 10 to 18 per cent chromium grades, further attention to welding these materials is unnecessary in this chapter. The summary includes welding precautions and the effect of welding on mechanical properties, also the effect of molybdenum, nitrogen, titanium, columbium, and other alloying elements.

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* E. H. Wyche, private communication.

G. AUTHORS' SUMMARY

1. Generally, the low-carbon 10 to 18 per cent chromium steels have a maximum carbon content of 0.12 per cent, although it is sometimes permitted to rise to 0.15 per cent. They are usually divided into two groups, *viz.*, those having 10 to 14 per cent chromium and those having 15 to 18 per cent chromium.

2. The steels of both groups are capable of being hot and cold worked, deep drawn, spun, welded, formed, and riveted. Both the cast and wrought 10 to 14 per cent chromium steels have useful mechanical properties and resistance to corrosion. They are air hardenable, and their final hardness can be varied over a wide range by variation of tempering temperatures. Optimum properties are obtained by oil or air hardening from about 955°C. (1750°F.) and tempering (depending upon the requirements) at temperatures extending up to 815°C. (1500°F.). The low-carbon 15 to 18 per cent chromium steels are not so subject to hardening as the lower chromium steels, but if their carbon content is increased beyond about 0.1 per cent, they can be hardened somewhat by quenching from similar temperatures. Although this grade is not so ductile and tough as the lower chromium grade, these alloys possess appreciable toughness and ductility when properly heat treated, especially in the wrought state.

3. The endurance limit of the 10 to 14 per cent chromium steels is about one-half the tensile strength. An important property of the steels is their good strength at moderately high temperatures as compared with that of carbon steels. The steels are resistant to mild forms of corrosion, such as those encountered in handling fruit juices, food products, and beverages. They are not resistant to staining in the atmosphere but become covered with a rust coating which does not penetrate progressively through the section. These low-carbon alloys, unlike those of the cutlery type (containing about 0.3 per cent carbon and 13 per cent chromium), do not depend entirely upon hardening and tempering for corrosion resistance; *i.e.*, the low-carbon steels in the annealed condition resist many corrosive media.

4. The low-carbon 15 to 18 per cent chromium steels are resistant to more severe corroding conditions and, if properly cleaned from time to time, maintain a bright surface during exposure to atmospheric conditions. They have been used extensively as trim on automobiles. The steels are quite resistant to concentrated nitric acid at both normal and elevated temperatures and are used commercially for this purpose.

5. Both grades possess appreciable resistance to oxidation at elevated temperatures. The 10 to 14 per cent chromium grade is generally recommended for temperatures up to 815°C. (1500°F.), and the 15 to 18 per cent chromium grade for temperatures up to about 870°C. (1600°F.).

6. The steels are suitable for welded construction, but unless certain precautions are employed, difficulties are likely to be encountered. The low-carbon 10 to 14 per cent chromium steels are subject to air hardening and, if softness, ductility, and toughness are required, it is necessary to anneal the welded structure. It is also preferable to preheat before welding. Good welds are obtainable in the 15 to 18 per cent chromium steels, but they are not so tough and ductile as those obtained in the lower chromium steels. It is preferable to anneal the welds in order to relieve strains. If high toughness is an important factor in welded construction, the chromium content of the weld should not exceed about 17 per cent, and the weld should be annealed also. Usually welds made in both types of steels are as resistant to corrosion as the base metal.

7. In the annealed condition both grades can be machined according to the usual processes employed for ordinary steels, although it is advisable to employ lower feeds and cutting speeds. Improved machining properties with somewhat reduced corrosion resistance can be obtained by the addition of certain other elements.

8. Additions of other metals have been made to the steels of both grades to improve certain properties. Nickel is especially suitable for improving the hardenability of the steels. Approximately 2 per cent nickel is added to the 10 to 14 per cent chromium steels containing a maximum of 0.12 per cent carbon to obtain the high degree of corrosion resistance associated with high hardness and strength. One to 2 per cent nickel is added to the 16 to 18 per cent chromium steels of relatively low carbon

content to increase hardenability; the result is a material of high strength and considerable corrosion resistance.

9. Sulphur is added to the 10 to 14 per cent chromium steels to improve machinability. Molybdenum improves machinability, workability, and forming properties, but, unlike sulphur, molybdenum increases rather than decreases corrosion resistance.

10. Additions of between 0.1 and 0.2 per cent aluminum are sometimes made to the 10 to 14 per cent chromium steels to obtain a reduction in air hardening. Aluminum, however, causes a decrease in the toughness of the steels.

11. Tungsten is added to the 10 to 14 per cent chromium steels to obtain high strength at elevated temperatures.

12. Silicon improves resistance to oxidation at elevated temperatures and, like aluminum, reduces air hardening. Up to 2.5 per cent silicon is frequently added to the 15 to 18 per cent chromium steels.

13. About 0.75 per cent silicon and about 1 per cent copper are added to the 15 to 18 per cent chromium steels to improve corrosion resistance and mechanical properties. When added to the 10 to 14 per cent chromium steels, about 1 per cent copper results in greater hardening and more uniform response to heat treatment. Additions of 8 to 10 per cent copper to the 15 to 18 per cent chromium steels have been proposed to improve corrosion resistance and mechanical properties.

14. Columbium, tantalum, and titanium additions in amounts sufficient to combine with the carbon reduce air hardening in the low-carbon 10 to 14 per cent chromium steels. These additions also improve the ductility of the low-carbon 15 to 18 per cent chromium steels, but they have not been used widely in the United States. The steels containing 2 per cent molybdenum with additions of either titanium or columbium have improved resistance to corrosion. Such steels are especially superior in weak chloride solutions, which normally cause the plain chromium steels to pit badly.

15. Nitrogen improves the hardening characteristics of both the 10 to 14 and the 15 to 18 per cent chromium steels. This improvement in hardenability is not accompanied by reduction of toughness; in fact, nitrogen additions to the extent of 0.08 to 0.14 per cent definitely improve the toughness of the 15 to 18 per

cent chromium steels. The nitrogen addition does not detract from the corrosion resistance of either type of steel.

16. The low-carbon 10 to 14 and 15 to 18 per cent chromium steels are among the most important stainless steels from the standpoint of industrial uses. Large quantities of the former have been employed as turbine blades in which resistance to the action of live steam and to deterioration by temperature effects is needed. These steels are especially suitable for resisting mild corroding media. They are used chiefly in the form of valve bodies, valve stems, rods, and trim. The 15 to 18 per cent chromium steels are used in the form of plate, rods, pipes, bolts, nuts, and rivets to resist nitric acid. Large quantities of these steels are produced in the form of polished strips and sheets for decorative purposes on both the exterior and the interior of structures. The steels are employed to resist corrosion by food products, and are used extensively in the form of trim for automobiles.

CHAPTER V

MEDIUM-CARBON STEELS CONTAINING 10 TO 18 PER CENT CHROMIUM

Structure and Transformations of Medium-carbon 10 *to* 18 *Per Cent Chromium Steels—Effect of Heat Treatment on Properties—Corrosion Resistance—Mechanical Properties at Elevated Temperatures—Modified* 10 *to* 18 *Per Cent Chromium Steels—Authors' Summary*

The medium-carbon 10 to 18 per cent chromium steels are within the ranges of composition proposed by Brearley* and Haynes† for use in the form of cutlery and for resisting corrosion. Brearley's steels were especially recommended for use as knife blades and contained 9 to 16 per cent chromium and less than 0.9 per cent carbon. The steels advocated by Haynes for corrosion resistance were to contain between 8 and 60 per cent chromium with up to 1 per cent carbon, his preferred limits being from 10 to 25 per cent chromium and 0.1 to 0.5 per cent carbon. Brearley made many useful observations on the properties of the steels proposed for cutlery and especially recommended a composition of about 13 per cent chromium and 0.3 per cent each of carbon, manganese, and silicon. He further recommended that, to resist staining, the finished knife should be hardened, tempered, and polished. The soundness of these recommendations has subsequently been well demonstrated, and, although a steel of higher carbon and chromium contents is now frequently employed, the original Brearley cutlery steel is still used widely.

In Brearley's early experiments the steels were melted in crucibles, but this method was soon abandoned for electric-furnace melting, the method used universally at present. General details of the melting practice for this grade of chromium steel are given in Chapter II (page 16). The usual procedure consists of melting a charge of high-grade scrap, removing the oxidizing slag, and finishing the heat under a lime-silica slag.

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* U. S. Patent 1,197,256, issued in 1916.

† U. S. Patent 1,229,404, issued in 1917.

Deoxidation is accomplished primarily by manganese and silicon, and the chromium is added usually as ferrochromium of suitable carbon content.

The hot working of the whole class of air-hardening steels, including the cutlery steels, is discussed in Chapter III. It is only necessary, therefore, to outline here such specific details as apply to the material containing 0.3 to 0.4 per cent carbon. These steels, like the rest of the air-hardening grades, are poured into small ingots. In hot working, they are among the most difficult to produce satisfactorily owing to the unusual combination of air hardening and red shortness.

The air-hardening tendency of high-carbon chromium steels was noted as early as 1892 by Hadfield(1) and has been studied for the 0.3 to 0.4 per cent carbon grade by a number of later investigators,(20,22,53) all of whom emphasized the necessity of thorough soaking, slow cooling, and careful heating.

In recent publications by Zieler(251) and by Morton and Rummler,(234) it is recommended that the medium-carbon cutlery grades be preheated in the neighborhood of 785°C. (1450°F.) prior to forging. These investigators gave the initial forging temperature as 980 to 1205°C. (1800 to 2200°F.) and advised the use of similar preheating and similar forging temperatures for subsequent rolling operations. By careful attention to the initial forging operation cracking has been eliminated(390) to the extent that intricate shapes and a wide range of sections can be produced.

A. STRUCTURE AND TRANSFORMATIONS OF MEDIUM-CARBON 10 TO 18 PER CENT CHROMIUM STEELS

The effect of heat treatment upon the physical characteristics of stainless steels has been studied widely. Guillet,(2) one of the early investigators, concluded that of the iron-chromium alloys with a carbon content of 0.4 per cent, those containing up to 6 per cent chromium were pearlitic, those containing from 6 to 15 per cent chromium were martensitic, and those containing above 15 per cent chromium were cementitic; such a classification is now known to be of doubtful validity.

68. Structure and Transformations.—It is shown in Volume I that the aggregate of alpha phase and chromium carbides in 12 per cent chromium steel, which is roughly analogous to pearlite

—and which is usually, but erroneously, called "pearlite"—contains about 0.3 per cent carbon. It is also shown that transformations are at temperatures greater than those of carbon steels; consequently, the minimum quenching temperature is higher. Further, chromium retards the diffusion of carbon; consequently, longer periods of heating and cooling are required to effect changes analogous to those in carbon steels. Another consequence is that practical transformation temperatures depend upon the thermal history of the steel as well as upon the rate of change of temperature; detailed experimental results are given in Volume I, Chapter IV. Most of these data were obtained before the publication of the work by Bain and Davenport (see Epstein[421]) on reaction rates of austenite. Although there are insufficient data on steels of the kind under discussion to permit adequate analysis of their rates of reaction, it is certain that the concepts of recent studies of the kinetics of solid-metal reactions are applicable. Since, however, the details of heat treatment of chromium cutlery steels are well known as a result of empirical study, quantitative data on their rates of transformation would be of doubtful practical utility. Qualitatively, it can be stated that the aforementioned retarded diffusion of carbon means retarded rates of transformation of chromium steels as compared with carbon steels.

69. Effect of Thermal Treatment.—Sections of the iron-chromium-carbon diagram given in Chapter III of the first volume of this monograph indicate that a temperature of 1000°C. (1830°F.) or less is sufficient to dissolve all free carbide in chromium cutlery steels. This is in agreement with the results of investigations on the effect of quenching temperature on the structure of these alloys, among which may be cited those of Seidell and Horvitz,(14) French and Yamauchi,(17) Monypenny,(21,22) Hall,(26) Guillet,(30) Rapatz,(54) and Bain.(133) If, however, the quenching temperature greatly exceeds 1000°C. (1830°F.), grain growth is appreciable, and mechanical properties become inferior to those resulting from lower quenching temperatures. Photomicrographs obtained by French and Yamauchi, given in Fig. 28, show clearly the large grains obtained upon high-temperature quenching; similar results were obtained by Rapatz. The latter showed also that in steels containing 14 per cent chromium and more than 1 per cent carbon a new constituent appears in the grain boundaries upon heating in excess of 1150°C. (2100°F.). This constituent is detrimental to the properties, such as hot rolling, of the steel; the damage cannot be repaired by heat treatment. It also may be the origin of the soft spots observed by Schoenmaker(106) and Bain(133) after quenching from temperatures approaching 1200°C. (2190°F.). (According to Rapatz, the constituent is "ledeburitic." Inspection of the phase diagram shows the likelihood of incipient melting.)

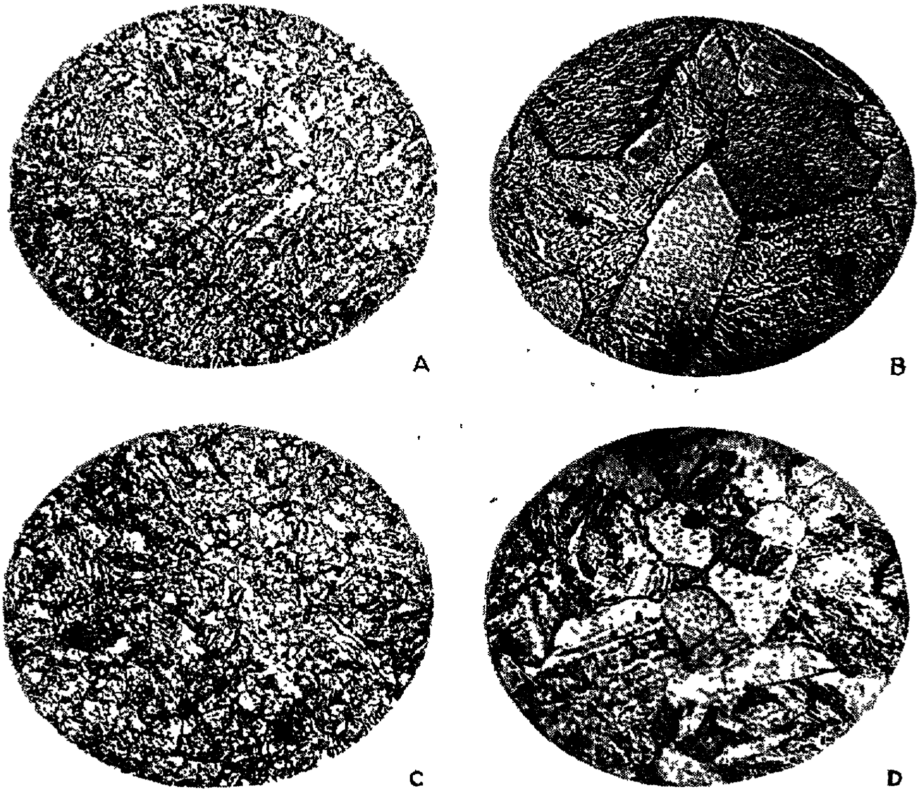

FIG. 28.—Grain growth in 0.3 per cent carbon, 13.5 per cent chromium steel. (*A*) oil quenched from 850°C. (1560°F.); (*B*) oil quenched from 1150°C. (2100°F.); (*C*) oil quenched from 955°C. (1750°F.) and tempered 30 min. at 435°C (815°F.); (*D*) oil quenched from 1150°C. (2100°F.) and tempered 30 min. at 540°C. (1100°F.). 500×. (*French and Yamauchi.*(17))

B. EFFECT OF HEAT TREATMENT ON PROPERTIES

70. Effect of Quenching and Tempering.—The effect of quenching from 650 to 815°C. (1200 to 1500°F.) on the hardness of a steel containing 0.33 per cent carbon, 0.46 per cent manganese, 0.45 per cent silicon, and 11.02 per cent chromium was investigated by Seidell and Horvitz.(14) Their results, repro-

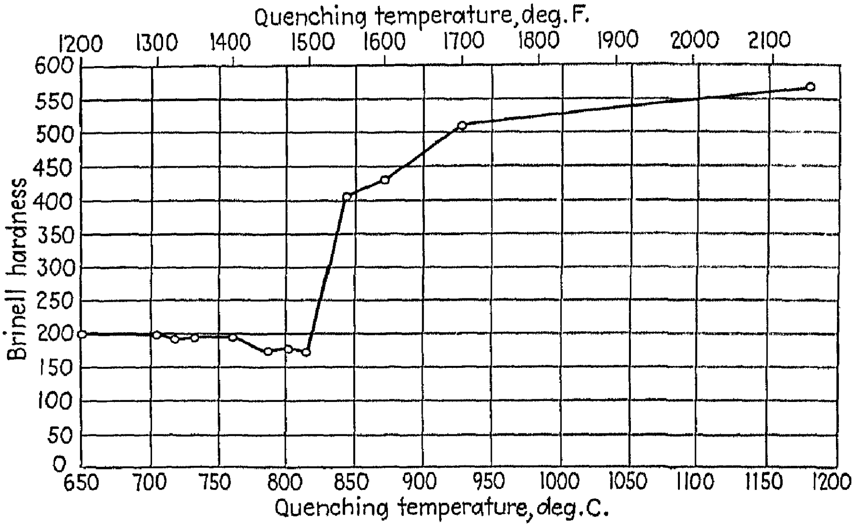

FIG. 29.—Effect of quenching temperature on the hardness of a steel containing 0.33 per cent carbon, 0.46 per cent manganese, 0.45 per cent silicon, and 11 02 per cent chromium. (*Seidell and Horvitz.*(14))

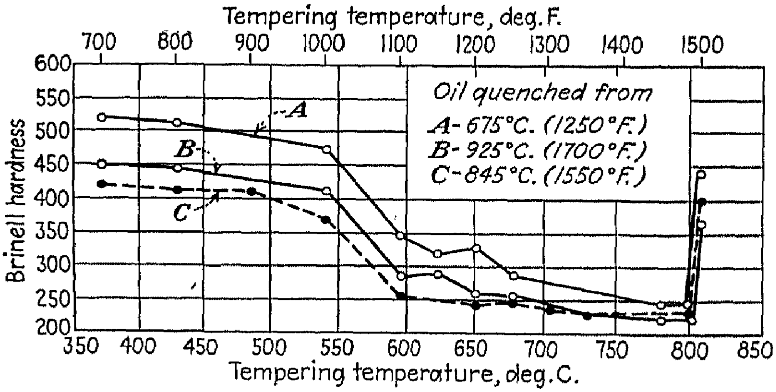

FIG. 30.—Effect of tempering on the hardness of an oil-quenched steel containing 0.33 per cent carbon, 0.46 per cent manganese, 0.45 per cent silicon, and 11 02 per cent chromium. (*Seidell and Horvitz.*(14))

duced in Fig. 29, indicate (*a*) that temperatures higher than 815°C. (1500°F.) are required to cause carbide solution and thus hardening, and (*b*) that the maximum hardness is practically reached after quenching from 925°C. (1700°F.).

Data obtained by the same investigators on the effect of tempering between 370 and 815°C. (700 and 1500°F.) on the hardness of the same steel previously quenched from 1175, 925, and 825°C. (2150, 1700, and 1550°F.) are reproduced in Fig. 30. They indicate that if the steel is to be tempered, not much is gained by quenching from 1175 instead of 925°C. (2150 instead of 1700°F.).

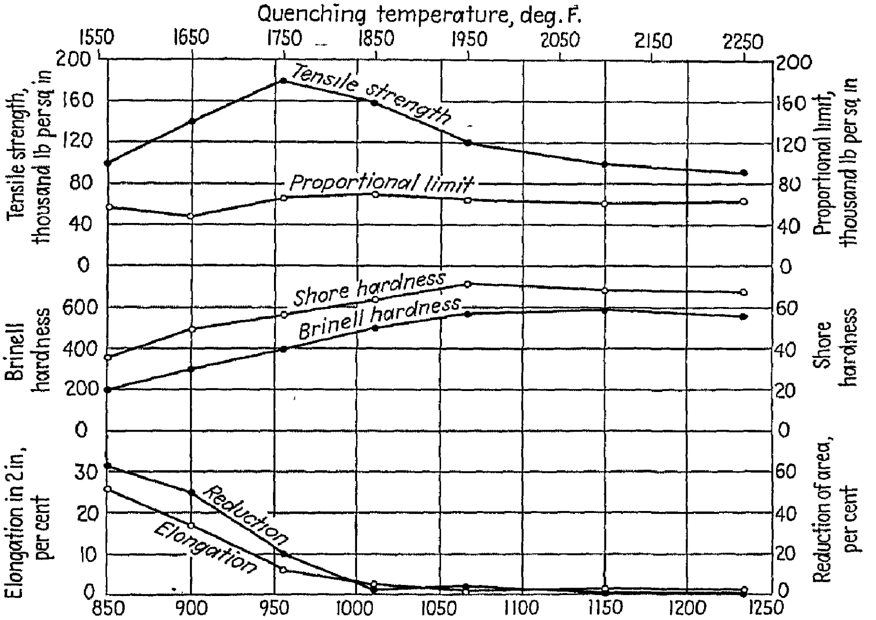

FIG. 31.—Effect of quenching temperature on the mechanical properties of a steel containing 0.27 per cent carbon, 0.69 per cent silicon, 0.52 per cent manganese, and 12.40 per cent chromium. (*French and Yamauchi.*(17))

Similar data (Figs. 31, 32, and 33), obtained by French and Yamauchi(17) on a steel containing 0.27 per cent carbon, 0.69 per cent silicon, 0.52 per cent manganese, and 12.40 per cent chromium, corroborate the fact that the best combination of mechanical properties is obtained by quenching from 955°C. (1750°F.) rather than from 1150°C. (2100°F.), followed by tempering as required. Steels tempered at 425°C. (800°F.) or below have somewhat greater hardness when quenched from 1150°C. (2100°F.) than when quenched from 955°C. (1750°F.). Use of the higher quenching temperature, however, results in very low elongation and reduction of area. This investigation also shows

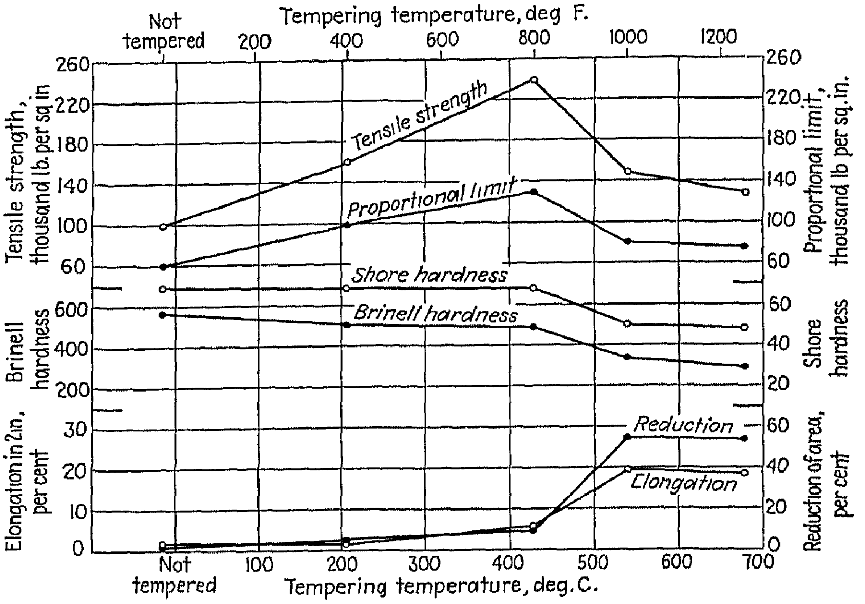

FIG. 32.—Effect of tempering on the mechanical properties of a steel containing 0.27 per cent carbon, 0.69 per cent silicon, 0.52 per cent manganese, and 12 40 per cent chromium, oil quenched from 1150°C. (2100°F.). (*French and Yamauchi.*[17])

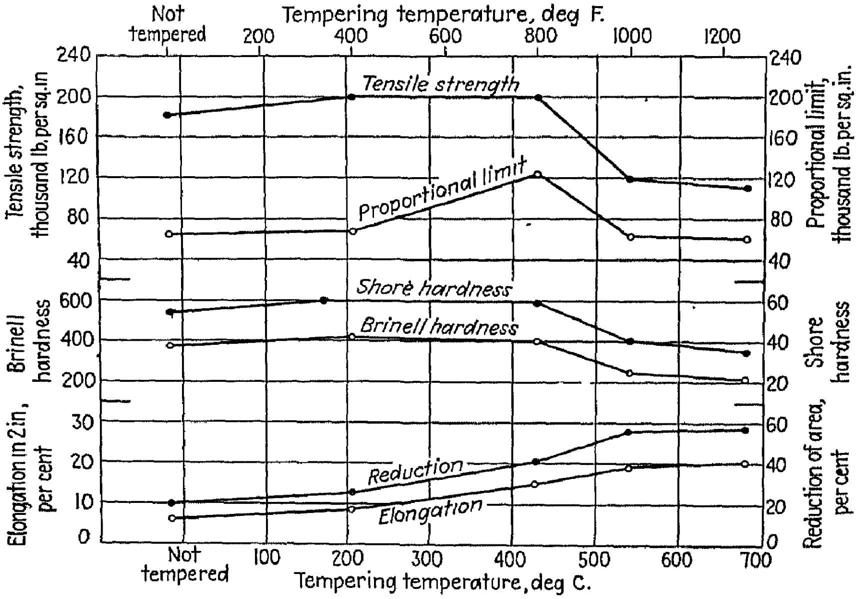

FIG. 33.—Effect of tempering on the mechanical properties of a steel containing 0.27 per cent carbon, 0.69 per cent silicon, 0.52 per cent manganese, and 12.40 per cent chromium, oil quenched from 955°C. (1750°F.). (*French and Yamauchi.*[17])

that tempering temperatures up to 425°C. (800°F.) can be used without decreasing strength or hardness. This is not true of a tempering temperature of 650°C. (1200°F.). According to Tour,(444) who conducted an extensive investigation, time at temperature is a very important factor in quenching and

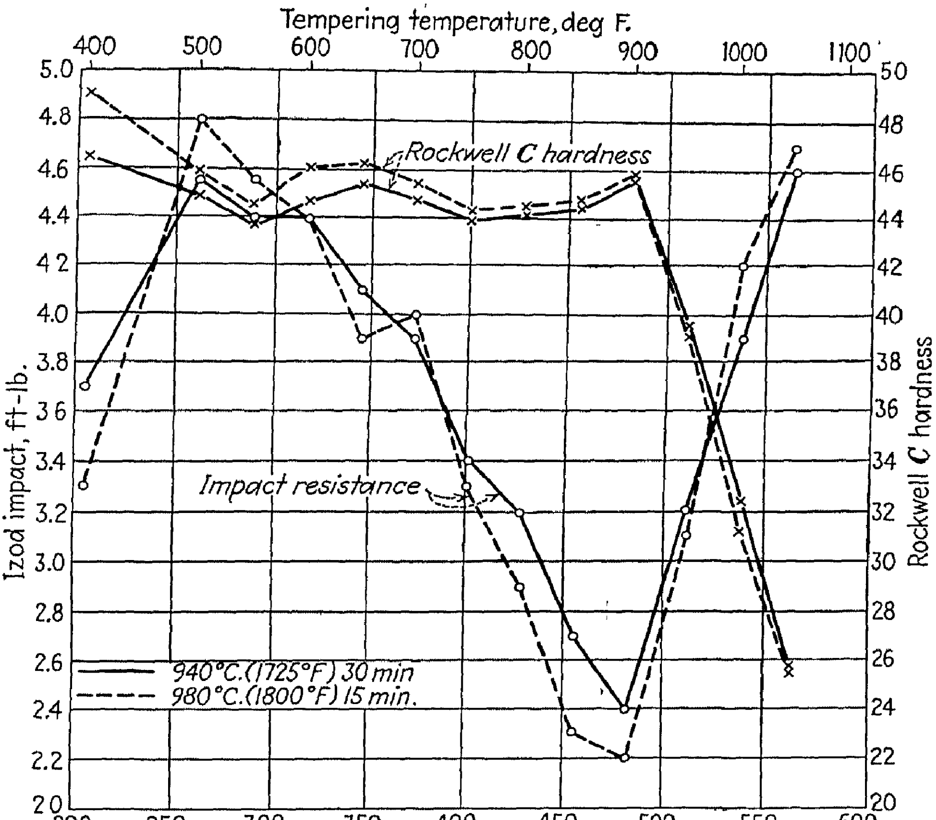

FIG. 34.—Effect of tempering on the hardness and impact resistance of an oil-quenched steel containing approximately 0.3 per cent carbon and 13.5 per cent chromium. (*Tour.*(444))

tempering small sections as, for example, stainless-steel springs. Variables were quenching temperature, time at quenching temperature, and tempering temperature; properties measured were Izod impact and Rockwell hardness. For specimens not over ½ in. in diameter it was found that maximum resistance to impact for a Rockwell *C* hardness of about 39 was obtained by soaking either 30 min. at 925 to 940°C. (1700 to 1725°F.) or 15 min. at 980 to 995°C. (1800 to 1825°F.) before quenching. Soaking 60 min. was found undesirable at all quenching temperatures. Tour selected a quenching temperature of 980°C. (1800°F.) and a soaking time of not more than 15 min. as economically desirable. The effect of tempering is shown by the

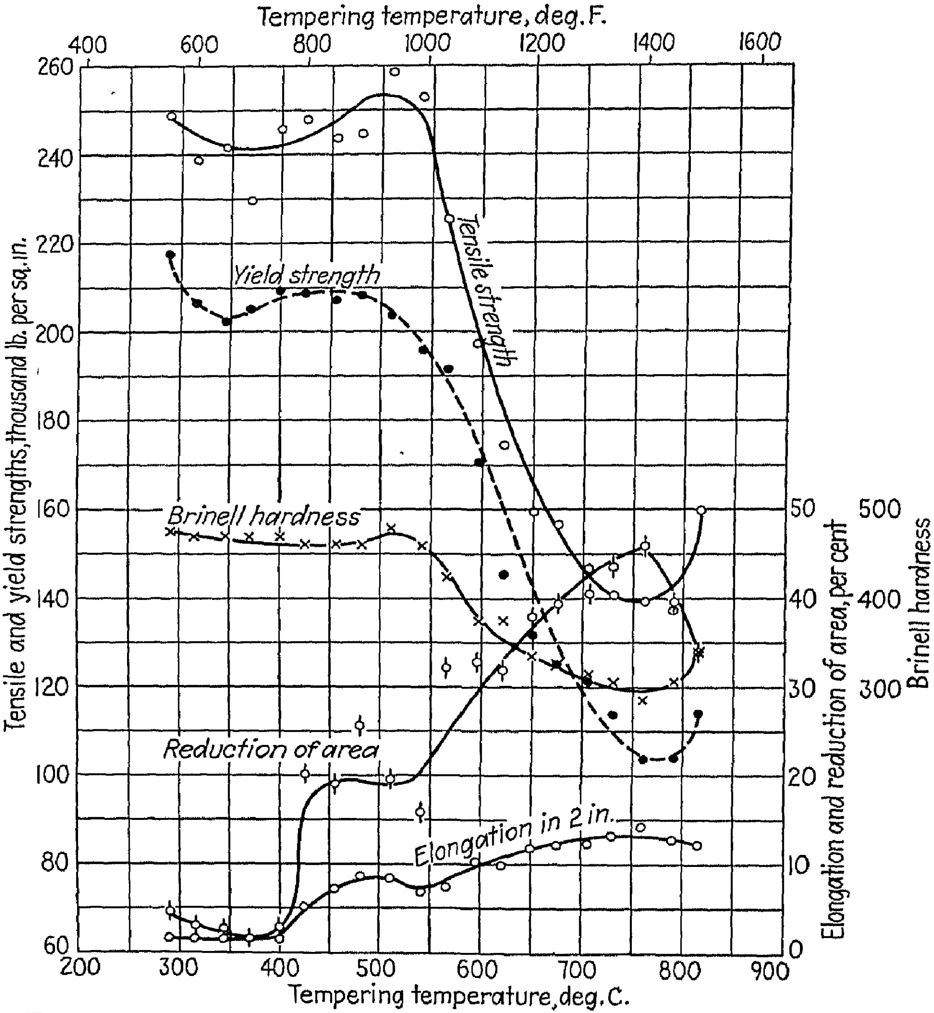

FIG. 35.—Effect of tempering on the mechanical properties of a steel containing approximately 0.3 per cent carbon and 13 per cent chromium, oil quenched from 995°C. (1825°F.) Plotting points are average values of 3 tests each of 10 heats. (*Based on data by Parmiter.*[53])

curves of Fig. 34; the range of temper brittleness is marked. For both quenching temperatures, maximum impact resistance resulted from tempering at 260 to 290°C. (500 to 550°F.) for 2 hr.

Guillet(30) reported that the best combination of strength, hardness, and toughness was obtained by oil quenching from 950 to 1000°C. (1740 to 1830°F.) followed by tempering at temperatures up to 495°C. (920°F.). He recommended that a steel containing 0.35 per cent carbon and 13 per cent chromium be annealed by heating slightly in excess of 900°C. (1650°F.) and cooling slowly or by heating for many hours at 750°C. (1380°F.) followed by either fast or slow cooling. Data on 10 heats reported by Parmiter(53) are plotted in Fig 35.

TABLE 32.—MECHANICAL PROPERTIES OF STAINLESS STEELS IN THE OIL-HARDENED AND TEMPERED CONDITION*

Composition, per cent			Tempered 1 hr. at		Tensile strength, lb./sq in.	Yield strength, lb /sq. in.	Proportional limit, lb /sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness	Modulus of elasticity, million lb./sq in †
C	Si	Cr	°C.	°F.								
Oil quenched from 950°C. (1740°F.)												
0.31	0.31	14.20	600	1110	146,100	120,100	87,000	18	55	29	305	32.0
			650	1200	123,500	96,000	69,100	23	60	37	262	32.9
			700	1290	108,500	78,100	58,000	28	67	63	228	31.6
0.43	0.13	12.37	600	1110	140,400	110,600	82,500	17	51	10	302	32.6
			650	1200	120,800	93,900	69,300	21	55	16	254	32.3
			700	1290	101,250	80,500	58,050	26	59	26	238	31.9
0.15	0.11	13.50	600	1110	132,400	110,200	82,250	21	63	27	285	31.3
			650	1200	110,200	88,000	64,900	24	66	39	233	31.5
			700	1290	97,500	72,100	60,200	28	69	107	206	31.6
Oil quenched from 1000°C. (1830°F.)												
0.31	0.31	14.20	600	1110	150,500	120,250	87,050	19	50	...	317	31.8
			650	1200	130,100	100,200	71,500	23	56	..	280	32.2
			700	1290	116,200	82,500	60,250	26	62	...	244	32.0
0.15	0.11	13.50	600	1110	136,800	105,400	76,100	22	63	...	271	30.8
			650	1200	110,800	89,500	65,000	25	65	...	236	31.1
			700	1290	86,900	72,500	58,050	29	67	...	207	30.9

* Abram.(43)

† Range of stress 8800 to 53,500 lb. per sq. in.

Stainless steels of this composition range are not restricted to cutlery; they are also used for many structural applications requiring corrosion resistance in combination with strength greater than that obtained in ordinary steels. Abram(43) determined the properties of such steels obtained by tempering in excess of 500°C. (930°F.) after oil hardening from 950 to 1000°C. (1740 to 1830°F.). Some of his results are given in Table 32.

They show that as the tempering temperature is increased from 600 to 700°C. (1110 to 1290°F.) strength decreases and elongation and reduction of area increase proportionally. There is, however, a rapid increase in impact resistance as the tempering temperature is increased from 650 to 700°C. (1200 to 1290°F.). The data further show that stainless steel has a relatively high modulus of elasticity. This was confirmed by Abram(306) in a later investigation.

71. Endurance.—Available data indicate that the endurance limit of stainless steels of the cutlery type tends to be about one-half the tensile strength, regardless of heat treatment. Thus, for nine annealed specimens containing 0.35 per cent carbon and 15.3 per cent chromium, Kjerrman(33) found an average value of 45,500 lb. per sq. in. (The tensile strength of such material in the annealed condition is about 92,000 lb. per sq. in.) More recently Bacon(257) reported an endurance limit (in rotary bending) of 53,800 lb. per sq. in. as compared with a tensile strength of 105,300 lb. per sq. in. for a steel containing 0.24 per cent carbon and 13.4 per cent chromium, oil quenched from 970 to 1000°C. (1780 to 1830°F.) and tempered at 580 to 750°C. (1075 to 1380°F.). More extensive data, obtained by McAdam,(48) are given in Table 33.

These steels have been subjected to corrosion-endurance tests also, as by McAdam,(102,151) Matthaes,(286) and Gough and Sopwith.(453) Such tests are difficult to evaluate, because there is evidence that there is no endurance limit under corrosive conditions. Gough and Sopwith, for example, found that a steel containing 0.25 per cent carbon, 17.1 per cent chromium, and 1.2 per cent nickel, heat treated to a tensile strength of 130,000 lb. per sq. in., failed under a load of about 40,000 lb. per sq. in. in 10^8 cycles (repeated and fluctuating stress, 3 per cent salt spray). However, despite laboratory tests, there are many examples of satisfactory service performance of these materials under conditions of repeated high stress and corrosion.

TABLE 33.—THE ENDURANCE OF SOME 12 TO 16 PER CENT CHROMIUM STEELS*

Composition, per cent			Cooled in	Tempered at		Tensile strength, lb./sq. in.	Torsional strength, lb./sq. in.	Endurance limit, for 10 million cycles, lb./sq. in.	
C	Cr	Cu		°C.	°F.			Rotating cantilever	Alternating torsion
0.08	11.78	..	Oil	480	900	166,500	....	74,000	
			Oil	540	1000	164,600	..	77,000	
			Oil	595	1100	109,500	....	61,000	
			Oil	705	1300	83,300	.....	45,000	
			Furnace	...	.	63,500	..	31,000	
0.42	12.26	....	Water	540	1000	171,500	110,500	88,000	43,000
			Water	650	1200	121,500	83,300	62,500	37,000
0.40	15.21	...	Water	480	900	164,300	110,500	84,500	40,000
			Water	565	1050	123,300	93,300	62,500	30,000
			Water	650	1200	115,700	73,400	59,500	30,000
			As received	...	....	110,000	70,600	49,500	24,000
0.61	15.81	1.10	Water	480	900	199,500	118,700	114,500	47,000
			As received	..	..	99,800	76,100	54,500	22,000
0.85	14.99	...	Water	480	900	230,300	150,400	104,000	65,000
			Water	565	1050	167,600	130,000	90,000	59,000
			Water	650	1200	131,500	87,200	72,500	37,000
			As received	...	....	111,000	84,200	50,000	21,500

* McAdam.(48)

72. Torsional Strength and Other Properties.—Results of torsional tests and other properties of cutlery steels have been reported by Austin(37) and Ludewig.(326) The latter's data on the torsional moduli (moduli of rigidity) of stainless steels at temperatures between 20 and 405°C. (70 and 760°F.) were obtained by a method which involves the use of the torsional moment on a straight sample and calculation of the modulus from the ratio of unit fiber stress to unit angular deformation.* The investigated steel contained 0.38 per cent carbon, 0.27 per cent manganese, 0.21 per cent silicon, 0.22 per cent nickel, and 14.07 per cent chromium; specimens were preheated to 675°C. (1250°F.), oil quenched from 980°C. (1800°F.), and tempered at 480°C. (900°F.). The torsional moduli were as follows:

Temperature of test		Torsional modulus, lb. per sq. in.
°C.	°F.	
26	79	11,700,000
170	340	11,480,000
220	430	11,200,000
280	540	11,070,000
350	660	10,720,000
405	760	10,290,000
475	890	9,800,000

This material is therefore one of those having a relatively small temperature coefficient of torsional modulus.

It is shown in Table 34 from Hatfield(59) that cutlery steels have relatively low thermal conductivity. This is responsible for the precautions necessary in heating and cooling this material and for the relatively long time necessary to permit the heat to penetrate to the center of a given cross-section. The coefficient of expansion is about the same as that of carbon steels; but electric resistivity is considerably higher. The effect of chromium on this property was investigated by Edwards and Norbury,(16) who concluded that chromium has little effect in annealed alloys until its amount exceeds 4.3 times the carbon percentage.

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* Based on the formula

$$G = S \div \frac{\theta}{L} = \frac{583PRL}{d^4\theta}$$

where P = load in pounds; R = lever arm in inches; L = length of sample in inches; d = diameter of sample in inches; θ = angle of twist in degrees; and G = torsional modulus in pounds per square inch.

TABLE 34.—VARIOUS PROPERTIES OF SOME STAINLESS CUTLERY STEELS CONTAINING 14 PER CENT CHROMIUM*

Carbon, per cent	Condition	Density, g. per cu. cm.	Mean coefficient of expansion, at 20 to 200°C., per °C.	Resistivity, microhm-cm.	Thermal conductivity, cal per sec per sq. cm. (°C per cm.)	Specific heat at 20°C., cal per g per °C.	Maximum permeability
0.33	Hardened and lightly tempered	7.73	0.0000109	63.2	0.0405	0.115	75
0.33	Hardened and tempered	7.67	0.0000116	77.7	0.0363	0.117	700
0.16	Hardened and fully tempered	7.69	0.0000115	74.6	0.0428	0.118	810

* Hatfield.(59)

Cutlery steels are somewhat erratically susceptible to temper brittleness. The data of Table 35, given by Monypenny,(191) are for steels containing about 0.3 per cent carbon and 13 per cent chromium. Specimens were air hardened from 900°C. (1650°F.), reheated to 700°C. (1290°F.), then either water quenched or furnace cooled. In every instance, the slowly cooled specimens were brittle in comparison with those rapidly cooled. Such behavior is not invariable, however; Monypenny also gave results on two heats of nearly identical composition,

TABLE 35.—EFFECT OF RATE OF COOLING AFTER TEMPERING ON RESISTANCE TO IMPACT OF 0.3 PER CENT CARBON, 13 PER CENT CHROMIUM STEELS*

Steel	Treatment	Brinell hardness	Izod impact, ft-lb.
1	Water quenched	251	45 45
	Furnace cooled	251	22 21 20
2	Water quenched	241	44 38 38
	Furnace cooled	235	25 23 25
3	Water quenched	255	35 38 30
	Furnace cooled	248	19 19 19
4	Water quenched	258	47 44 38
	Furnace cooled	255	37 33 30

* Monypenny.(191)

but only one showed any evidence of temper brittleness. The reason for such behavior is not clear. Tour,(444) whose data are discussed on page 123, found marked temper brittleness at 455 to 480°C. (850 to 900°F.).

Brittleness due to air hardening may be encountered in fabricating the steels. In general, stainless steel can be welded by any of the well-known processes (except hammer welding) if a suitable flux is used; but, in the case of cutlery steels, air hardening causes brittleness in the weld and in the zone adjacent to the weld. To eliminate this, it is necessary to anneal the welded structure, and then harden and temper. Air hardening also occurs in brazing. In soldering or silver soldering, the usual precautions are employed; but a stronger flux and a slightly higher temperature should be used than for carbon steels. This temperature is generally well below the critical air-hardening temperature. The literature on welding the cutlery steels has been reviewed recently by Spraragen and Claussen.(527)

C. CORROSION RESISTANCE

The outstanding characteristic of stainless cutlery steels is their resistance to corrosion. This resistance is greatest when the steel is hardened by quenching and when a polished surface is exposed. Quenching strains are relieved by tempering cautiously, because appreciable softening of the steel spells lost resistance to corrosion.

Perhaps the most exhaustive summary of information on corrosion tests of cutlery steels was given by Monypenny.(191) That given here, however, is thought to be adequate for most purposes.

73. Effect of Tempering.—Work by Hatfield,(12) Monypenny,(22) Parmiter,(53) and others proved that high tempering temperatures are dangerous for the corrosion resistance of plain chromium cutlery steels and that, specifically, temperatures higher than 500°C. (930°F.) should be avoided if the maximum corrosion resistance is to be maintained. Representative data, obtained by Parmiter(53) to show the effect of tempering on resistance to various media, are reproduced in Table 36.

The generally accepted explanation of the effect of tempering is that the corrosion resistance of any stainless steel is a function of the chromium in solution in the steel. If a portion of the chromium is combined with carbon in the form of carbides of chromium as separate constituents, the solid solution is depleted of chromium and the metal has less corrosion resistance. This is the case in tempering above 480°C. (900°F.). Also, the work of Evans(111) indicates that the resistance to corrosion of the high-chromium steels depends on the formation of a continuous film of oxide on the surface. When the carbides are precipitated in a finely divided state, as is the case on tempering above 480°C. (900°F.), local stresses are imposed which may seriously affect the film and thus reduce corrosion resistance.

TABLE 36.—EFFECT OF TEMPERING ON RESISTANCE TO STAIN*

Tempering temperature		Brinell hardness	Scleroscope hardness	Stain-resistance index†, per cent, upon exposure to		
°C.	°F.			10 % $CuSO_4$	33.5 % nitric acid	5 % acetic acid
Not tempered		600	86	100	100	100
205	400	590	86	100	100	100
260	500	600	86	100	100	100
315	600	590	85	100	100	100
370	700	590	85	100	100	100
425	800	590	85	100	100	100
480	900	550	83	95	100	95
510	950	500	78	95	100	90
540	1000	475	76	95	100	90
565	1050	450	73	90	100	90
595	1100	400	67	85	100	90
620	1150	375	64	80	100	90
650	1200	350	61	70	95	85
675	1250	325	57	65	95	85
705	1300	315	52	60	95	85
760	1400	275	48	50	95	85
815	1500	325	57	25	90	80
Annealed		185	32	25	90	75

* Parmiter (53)

† The stain-resistance index was determined from the appearance of the stains on samples 1.5 in. round by 1 in. thick, oil quenched from 995°C. (1825°F.) and tempered as shown, after exposure to $CuSO_4$ for 6 min., to nitric acid for 2 min., and to acetic acid dried on. It denotes approximately the comparative efficiency in percentage.

74. Resistance to Organic Acids.—The wide use of these steels as cutlery has demonstrated their satisfactory resistance to the chemical compounds encountered in foods of various types.

Investigators agree that acids present in oranges, lemons, apples, tomatoes, and the like do not attack the steels, and that alkalis, as in soaps, lyes, ammonia, and similar cleansing media, likewise produce no reaction. It has been stated that these steels are not corroded by blood, alcohols, carbonates, sugar solutions, boric acid, oleic acid, stearic acid, and steam. Hydrochloric acid, chlorine, chlorides, iodides, and sulphuric acid, however, and some sulphates, do attack the steels readily, as does acetic acid in the concentrations found in some vinegars. The general immunity of these steels to organic reagents is responsible for their wide use in the household.

75. Acid, Salt-water, and Atmospheric Corrosion.—It was discovered very early(1) and fully confirmed by Hatfield(38) that, in general, the plain high-chromium steels are resistant to oxidizing media, such as nitric acid and the atmosphere, but are not so resistant as carbon steel to reducing media. Hatfield(38) made corrosion tests on samples of relatively pure iron and of iron alloyed with chromium and nickel and concluded that chromium increased the solubility of iron in sulphuric and hydrochloric acids but materially decreased its solubility in nitric acid.

Rawdon and Krynitzky(34) tested annealed steels containing from about 4 to slightly over 13 per cent chromium in dilute hydrochloric acid and in the atmosphere. They concluded that the reactions in hydrochloric acid have no relation to the behavior of the steels in the atmosphere. In the hydrochloric acid tests, all the steels were badly attacked, but practically no attack occurred in atmospheric-corrosion tests when the steels contained about 13 per cent chromium. They further found, as did Cournot(217) and many others, that under atmospheric conditions the greatest corrosion resistance was obtained with polished surfaces. The resistance of hardened and tempered stainless steel to the atmosphere after long periods of exposure was reported by Hadfield.(31) He observed that in the industrial atmosphere near Sheffield, England, a 13.5 per cent chromium steel became tarnished but did not rust progressively. He further observed that the steels tended to pit in sea water, even though they were highly polished. In similar experiments, Friend(138) found that annealed, descaled, and polished samples of these steels, partly immersed in sea water, were badly attacked near the water line, and that completely immersed samples, exposed to the sea water for a period of approximately five years, exhibited considerable pitting.

Parmiter(121) studied the resistance of cutlery steels when exposed for many months to all types of weather: wet, dry, frost, and snow. The polished surfaces of the steels remained bright. Samples placed in fresh water containing a high percentage of dissolved oxygen also remained unaffected. When exposed to an industrial atmosphere, however, the steels tarnished readily; according to Parmiter, this was due to the presence of sulphur compounds and other furnace-combustion products. He also stated that stainless steel is no exception to the rule that two dissimilar metals placed in contact with each other in an electrolyte produce galvanic action and corrosion. He showed that when stainless steel was used in contact with metals such as copper, bronze, and brass tarnishing and pitting resulted.

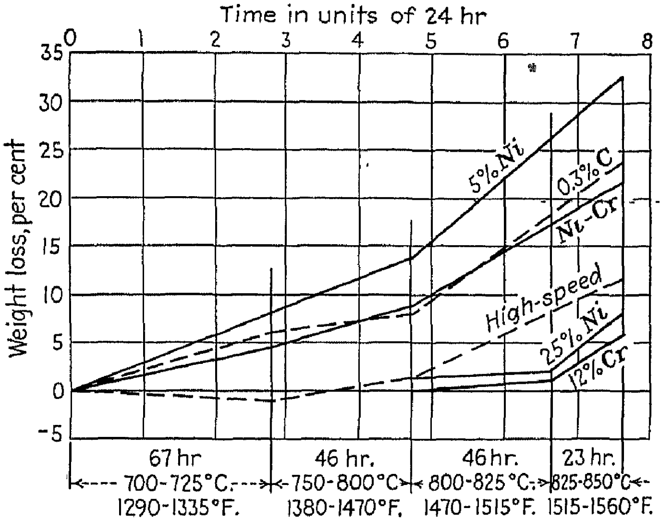

FIG. 36 —Scale resistance of various steels. The 12 per cent chromium steel contained 0.32 per cent carbon. (*Monypenny*.(41))

76. Oxidation Resistance.—In general, high-chromium stainless steels resist oxidation at temperatures at which carbon and low-alloy steels scale rapidly. Monypenny(41) reported their superiority over other steels at temperatures as high as 825 to 850°C. (1515 to 1560°F.). His data, presented in Fig. 36, were obtained by heating ⅝-in. diameter rounds in a gas-fired muffle furnace. The temperature was raised at regular intervals, and the samples were withdrawn and weighed every 24 hr. The weight loss is reported as percentage of the original weight.

Similar results were obtained by Dickenson,(27) who exposed polished cylinders of an oil-quenched steel containing 0.26 per cent carbon and 14.7 per cent chromium to various temperatures for a total of 100 hr. At intervals of about 5.5 hr. the specimens were removed from the furnace, cleaned, and then reheated. The data given in Table 37 are, therefore, for the initial scaling period. Data on a 0.3 per cent carbon steel are given for comparison.

TABLE 37.—SCALING RATES OF TWO STEELS AT VARIOUS TEMPERATURES*

Temperature		Weight increase, mg. per sq. dm. per day	
°C.	°F.	0.3 % C steel	14.7 % Cr steel
575	1065	1,004	Nil
675	1245	2,976	186
725	1335	6,696	372
775	1425	13,392	744
875	1605	37,200	2,604

* Dickenson.(27)

It was pointed out by Hatfield(86) that oxidation resistance is a function of the composition of the atmosphere as well as of temperature. It is shown in Table 38 that, in oxygen, a 13 per cent chromium steel is fairly resistant to scaling up to about 900°C. (1650°F.), but if the temperature is raised to 1000°C. (1830°F.), it oxidizes rapidly. It is apparent that if steam, carbon dioxide, or sulphur dioxide is present in large quantities, the upper limit for satisfactory resistance is about 800 instead of 900°C. (1470 instead of 1650°F.). The effect of the atmosphere upon scaling at elevated temperatures was emphasized by Waeser,(341) who found that high-chromium steels would not resist scaling at temperatures above 500°C. (930°F.) if appreciable quantities of hydrogen sulphide gas were present. Pfeil(122) made a comprehensive study of the oxide formed when a steel containing 12.23 per cent chromium was exposed to temperatures up to 1000°C. (1830°F.). He found that three distinct oxide layers were formed; the middle and outer layers contained only a fraction of 1 per cent of chromium, the oxide layer immediately adjacent to the steel, however, contained approximately 3.5 times as much chromium as iron. This indicates that chromium acts to prevent the metal from becoming progressively oxidized because sufficient chromium concentrates in the innermost oxide layer to form an impervious coating.

TABLE 38.—CORROSIVE ATTACK OF STAINLESS VERSUS CARBON STEEL BY VARIOUS GASEOUS MEDIA AT ELEVATED TEMPERATURES*

Steel	Medium	Weight increase, mg. per sq. dm. per day, at			
		700°C. (1290°F.)	800°C. (1470°F.)	900°C. (1650°F.)	1000°C. (1830°F.)
G†	Oxygen	1,042	2,976	8,341	17,086
K†	Oxygen	223	190	278	9,130
G	Steam	367	2,197	7,493	23,105
K	Steam	52	57	1,490	3,984
G	Carbon dioxide	1,002	3,673	7,491	9,346
K	Carbon dioxide	81	87	1,604	6,228
G	Sulphur dioxide	987	4,164	17,700	‡
K	Sulphur dioxide	39	104	993	5,861

* Hatfield.(86)

† Steel *G* contained 0.17 per cent carbon, 0.18 per cent silicon, and 0 67 per cent manganese and was normalized at 900°C (1650°F) Steel *K* contained 0 32 per cent carbon, 1 32 per cent silicon, 0.25 per cent manganese, and 13.12 per cent chromium and was oil quenched from 1000°C (1830°F) and tempered at 800°C. (1470°F.).

‡ Completely converted to sulphide.

D. MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES

There are few data on the properties of stainless cutlery steels at elevated temperatures; these consist mostly of results of short-time tensile tests. As early as 1920, Monypenny(22) reported that on this basis the stainless steels are considerably stronger than mild carbon steel at temperatures ranging from 600 to 850°C. (1110 to 1560°F.). Results obtained by French(29) on a quenched and tempered steel containing 0.31 per cent carbon and 12.75 per cent chromium are shown in Fig. 37. Other short-time results were reported by Henshaw,(87) Hatfield,(101) and Ranque and Henry(333) among others; they are not reproduced because it is generally conceded that such data alone are of little use. Gough,(223) for example, quoted the data of Table 39 to illustrate the unreliability of short-time tests.

TABLE 39.—ELEVATED-TEMPERATURE TESTS OF A STEEL CONTAINING 0.29 PER CENT CARBON AND 13.7 PER CENT CHROMIUM*

Temperature		Stress, lb. per sq. in., for			
°C.	°F.	Fracture in 10 min.	Fracture in about 5 days	Fracture in about 25 days	Extension of 10^{-5} in. per in. per day after about 40 days
400	750	85,200	69,400	62,800	43,700
500	930	69,400	32,500	29,100	10,100
600	1110	46,000	11,200	7,800	1,800

* Gough.(223)

77. Creep Tests.—Data of long-time tests on stainless cutlery steels are scarce also. The first on record were published by Dickenson(27) in 1933, but they are not of the kind now thought to be useful. Later data, in terms of stress for an extension of 10^{-5} in. per in. per day (numerically equivalent to about 0.4 per cent per 10,000 hr.), obtained by Inglis and coworkers(146,170) on quenched and tempered steels containing 0.27 per cent carbon and 14 to 15 per cent chromium, are 49,000 lb. per sq. in. at

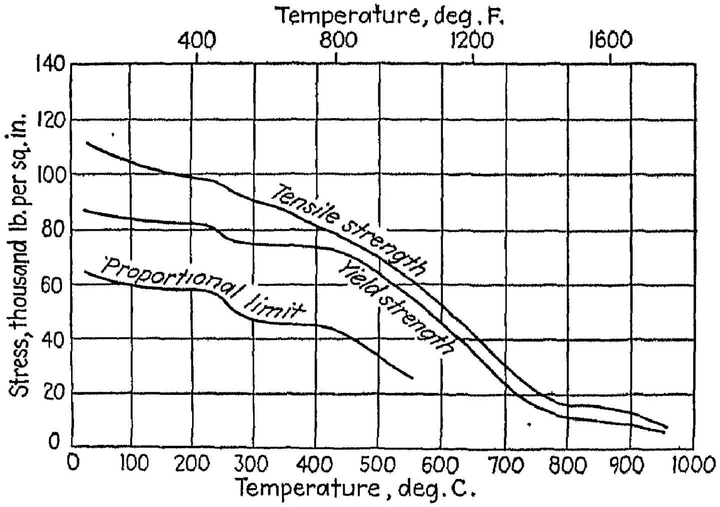

FIG. 37.—Short-time elevated-temperature properties of a steel containing 0.36 per cent carbon and 11.20 per cent chromium. (*French.*(29))

350°C. (660°F.), 29,000 lb. per sq. in. at 450°C. (840°F.), and 4500 lb. per sq. in. at 550°C. (1020°F.).

Other (unpublished) creep data, for 13 per cent chromium steel, are given in Table 40. The specimens were normalized at 900°C. (1650°F.), oil quenched from 980°C. (1800°F.), and tempered at 675°C. (1250°F.). The stress for a creep rate of 1 per cent per year (8760 hr.) was substantially unchanged for temperatures up to 290°C. (550°F.). At a temperature of 650°C. (1200°F.) it was slightly higher than that for a carbon steel containing about 0.4 per cent carbon but very much lower than for an austenitic chromium-nickel steel.

TABLE 40.—RESULTS OF CREEP TESTS ON A STEEL CONTAINING 0.31 PER CENT CARBON AND 12.90 PER CENT CHROMIUM

Temperature of test		Creep stress, lb. per sq. in., for an extension of 1 per cent per year
°C.	°F.	
20	70	78,500
150	300	73,500
290	550	73,500
650	1200	1,305
785	1445	458

E. MODIFIED 10 TO 18 PER CENT CHROMIUM STEELS

So far, this chapter has dealt with cutlery steels of the approximate composition originally advocated by Brearley, *viz.*, 13 per cent chromium and 0.3 per cent each of carbon, manganese, and silicon. There are two major reasons for the retention of this composition. When smaller amounts of carbon are employed with 13 per cent chromium, or higher chromium with 0.3 per cent carbon, the steel does not become hard enough; and if higher carbon contents are employed to secure greater hardness, toughness is lacking. Lower chromium sacrifices corrosion resistance. However, as stated by Parmiter,(121) investigation of the combined effects of increased carbon and increased chromium has shown the usefulness of such materials and has resulted in their industrial development.

78. Effect of High Carbon.—The high-carbon grade of stainless chromium steel contains about 17 per cent chromium and 0.7 to

1 per cent carbon. It was developed for cutlery and surgical instruments for which high cutting quality combined with great resistance to staining is required. Such steels are used also for ball bearings, pump valves, superheated-steam equipment, oil pumps, laundry machinery, and milk-bottling equipment. On the whole, they are similar to the 0.3 per cent carbon grade.

Steels containing 17 per cent chromium and 1 per cent carbon were described by *Morton and Rummler*.(234) *Certain details* of their treatment are worthy of note. In forging, it is usual to preheat at 785 to 815°C. (1450 to 1500°F.) to remove casting strains. The metal has a tendency to tear when hot, and it is usually forged at temperatures between 1205 and 980°C. (2200 and 1800°F.). Morton and Rummler recommended heating the forging at 870°C. (1600°F.) and cooling slowly to ensure freedom from cracking. Results of oil-quenching experiments are reported in Table 41. They show that maximum hardness is reached at a temperature of 1040°C. (1900°F.). This may be compared with the data of Monypenny,(191) reproduced in Fig. 38, which indicate that in steels of somewhat lower carbon content greatest hardness results after quenching from 1050 to 1100°C. (1920 to 2010°F.). Treatment at this temperature range is also required for wrought products to eliminate banded carbides in the microstructure. Morton and Rummler observed that sections hardened above 1050°C. (1925°F.) exhibited grain growth and were not so tough as those quenched from the slightly

TABLE 41.—EFFECT OF OIL QUENCHING FROM DIFFERENT TEMPERATURES ON THE HARDNESS OF A STEEL CONTAINING ABOUT 1 PER CENT CARBON AND 17 PER CENT CHROMIUM*

Quenching temperature		Rockwell *C* hardness
°C.	°F.	
980	1800	55 to 58
1010	1850	56 to 59
1025	1875	57 to 60
1040	1900	61 to 63
1050	1925	59 to 63
1065	1950	59 to 62

* Morton and Rummler.(234)

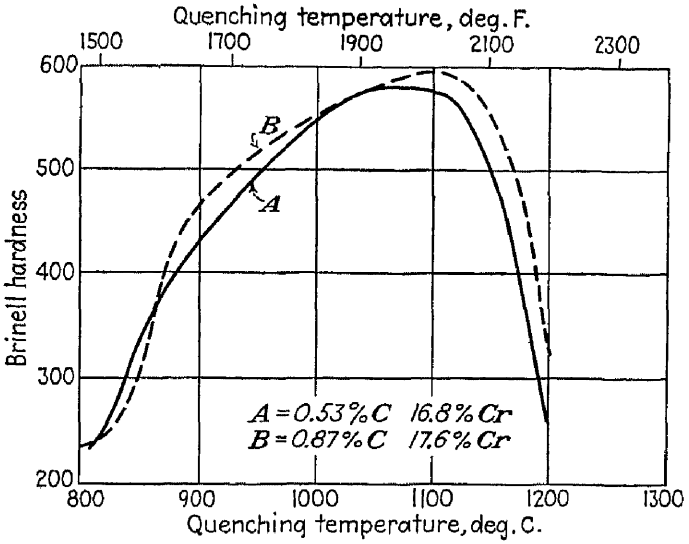

FIG. 38.—Effect of quenching temperature on the Brinell hardness of medium- and high-carbon 17 per cent chromium steels. (*Monypenny.*[191])

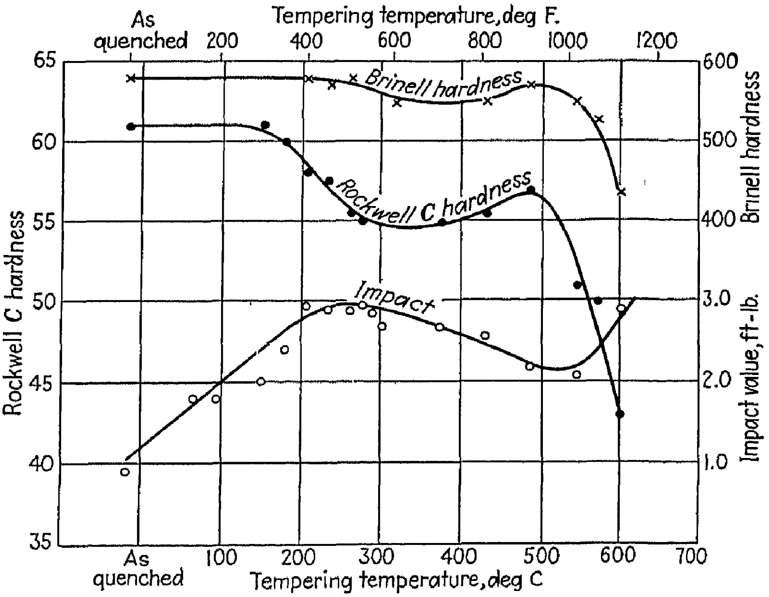

FIG. 39.—Effect of tempering on the hardness and impact resistance of steel containing 1 per cent carbon and 17 per cent chromium, oil quenched from 1040°C. (1900°F.). (*Morton and Rummler.*[284])

lower temperatures. Their data on the effects of tempering at different temperatures on the hardness and toughness of a steel of this type after oil quenching from 1040°C. (1900°F.) are given in Fig. 39. It was concluded that to obtain optimum hardness with maximum toughness, the hardened steel should be tempered at below 425°C. (800°F.) and either quenched or slowly cooled; that if the tempering temperatures are above 595°C. (1100°F.), tempering should be followed by quenching rather than by slow cooling; and that tempering between 440 and 580°C. (825 and 1075°F.) causes a decrease in toughness, so that this range of temperatures should be avoided for tempering purposes.

79. Effect of Silicon.—The effect of silicon in amounts greater than those normally employed for deoxidation is to raise the temperature of transformation and reduce the air-hardening capacity of the steels. When added to the extent of 2 to 3 per cent, it increases grain size. Silicon lowers the hardness of quenched cutlery steels, but after hardening and tempering, the higher silicon steels are harder than similar steels low in silicon. Impact toughness is reduced by silicon.

Abram(43) investigated the properties of steels with normal and relatively high silicon after oil hardening from 950 and 1000°C. (1740 and 1830°F.) and tempering between 600 and 700°C. (1110 and 1290°F.). His data, given in Table 42, show that as the silicon content is increased to slightly over 1 per cent the steels become sluggish both on hardening and on tempering, and the impact toughness is reduced materially. Later work by Oertel and Würth(93) on 15 per cent chromium steels containing up to 5 per cent silicon and 0.5 per cent carbon confirmed that with more than 1 per cent silicon present hardening capacity was greatly reduced. It was also shown that silicon additions raised the temperatures to which the steels must be heated for hardening and that with more than 1 per cent silicon, fabrication was more difficult. With as much as 3 to 5 per cent silicon, the steels were non-hardenable and brittle.

Concerning the effect of silicon on corrosion resistance, Abram(43) concluded that amounts slightly above 1 per cent did not improve the resistance to atmospheric corrosion. In medium-carbon 14 per cent chromium steels, however, he found a slight improvement in resistance to sea water, provided the steels were hardened, tempered, and polished.

TABLE 42.—EFFECT OF SILICON ON THE MECHANICAL PROPERTIES OF MEDIUM-CARBON 13 TO 14 PER CENT CHROMIUM STEELS*

Composition, per cent			Tempered 1 hr. at		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness	Modulus of elasticity, million lb./sq. in.†
		Cr	°C.	°F.								
Oil hardened from 950°C. (1740°F.)												
0.15	0.11	13.50	600	1110	132,400	110,200	82,250	21	63	27	285	31.3
			650	1200	110,200	88,000	64,900	24	66	39	233	31.5
			700	1290	97,500	72,100	60,200	28	69	107	206	31.6
0.17	1.35	13.90	600	1110	103,100	67,400	51,200	27	62	9	229	29.3
			650	1200	99,200	67,100	49,200	27	64	13	222	29.7
			700	1290	94,100	61,300	44,700	32	67	14	210	29.5
0.31	0.31	14.20	600	1110	146,100	120,100	87,000	18	55	29	305	32.0
			650	1200	123,500	96,000	69,100	23	60	37	262	32.9
			700	1290	108,500	78,100	58,000	28	67	63	228	31.6
0.35	1.43	14.70	600	1110	140,000	109,500	75,900	19	54	13	296	32.5
			650	1200	121,000	99,100	75,900	22	55	17	274	32.0
			700	1290	120,000	86,000	71,500	27	59	23	249	32.0
Oil hardened from 1000°C. (1830°F.)												
0.15	0.11	13.50	600	1110	136,800	105,400	76,100	22	63	...	271	30.8
			650	1200	110,800	89,500	65,000	25	65	...	236	31.1
			700	1290	86,900	72,500	58,050	29	67	...	207	30.9
0.17	1.35	13.90	600	1110	138,500	99,000	64,500	22	57	...	276	29.8
			650	1200	119,900	65,900	62,500	24	60	...	259	30.5
			700	1290	111,500	79,000	56,000	27	61	...	238	28.5
0.31	0.31	14.20	600	1110	150,200	120,100	87,000	19	50		317	31.8
			650	1200	132,100	100,100	71,500	23	56	...	280	32.2
			700	1290	116,500	82,500	60,000	26	62	...	244	32.0
0.35	1.43	14.70	600	1110	155,000	122,500	93,500	19	50		326	31.8
			650	1200	145,500	111,900	85,000	21	53	...	301	31.6
			700	1290	130,000	95,000	76,000	24	57	...	270	31.3

* Abram (43)

† Range of stress 8800 to 53,500 lb. per sq. in.

Monypenny(191) used the vinegar spot test on two steels, one of standard cutlery composition, the other one containing 1.26 per cent silicon (see Table 43 for detailed composition). He concluded that silicon has little effect on the stain resistance of this type of chromium steel. After oil quenching from 900°C.

(1650°F.) the standard steel, of Brinell hardness 495, was not attacked, while the high-silicon steel, similarly heat treated and of a Brinell hardness of 286, was stained slightly. However, raising the quenching temperature to 950°C. (1740°F.) increased the hardness values to 555 and 430 Brinell respectively for the steel without and with silicon; and in this condition, both steels were unattacked. After hardening and tempering, both steels were stained slightly, and similar results were obtained after annealing.

TABLE 43.—EFFECT OF SILICON ON THE ACID RESISTANCE OF 13 PER CENT CHROMIUM STEEL*

Acid used	Strength	Weight loss, g. per sq. m. per hr.	
		Steel *A*†	Steel *B*†
Hydrochloric	10 per cent	2.5	2.65
Nitric	Normal	5.6	2.4
Sulphuric	5 per cent	7.1	2.8
Sulphuric	35 per cent	112	30.3
Sulphuric	50 per cent	6.0	8.7
Acetic	5 per cent	0.61	0.63
Citric	6 per cent	1.1	0.5
Oxalic	Normal	0.3	0.3

* Monypenny (191)

† Steel *A* contained 0.39 per cent carbon, 0.11 per cent silicon, and 13.0 per cent chromium; steel *B* contained 0.38 per cent carbon, 1.26 per cent silicon, and 13.8 per cent chromium

According to the data of Table 43, the effect of slightly more than 1 per cent silicon on the acid resistance of standard cutlery steel is not uniform. Monypenny(191) pointed out that, although improvement by silicon in resistance to dilute nitric acid is indicated in the table, the presence of more than the normal amounts of silicon in cutlery steels is detrimental to resistance to hot concentrated nitric acid solutions. In this connection, it is interesting that Evans(111) found that the addition of about 3.5 per cent silicon to iron reduced its passivity in concentrated nitric acid.

Oertel and Würth(93) reported a series of corrosion tests on steels of the composition shown in Table 44. They found that silicon causes a slight increase of resistance to hydrochloric and nitric acids and has little effect on resistance to acetic acid and sea water. They also conducted a series of scaling tests (Table 44) which show that relatively large percentages of silicon produce a marked improvement in resistance to oxidation at 900°C. (1650°F.). Mechanical-property values were found to be lowered by silicon.

TABLE 44.—RESULTS OF 45-HR. OXIDATION TESTS AT 900°C. (1650°F.)*

Composition, per cent			Amount of oxidation
C	Si	Cr	
0.10	0.44	15.10	Oxidized
0.15	0.32	14.76	Oxidized
0.28	0.25	15.45	Oxidized
0.08	1.02	13.50	Oxidized fully
0.11	2.78	14.41	Smooth gray, without scale
0.08	3.84	13.38	Smooth gray, without scale
0.15	4.70	14.96	Smooth gray, without scale
0.38	0.86	15.44	Oxidized fully
0.36	2.88	15.44	Smooth gray, without scale

* Oertel and Würth.(93)

80. Effect of Manganese.—Becket* suggested that, in small percentages, manganese might act similarly to nickel in increasing the hardening capacity of steels containing 13 to 15 per cent chromium. His actual experiments were conducted on material containing somewhat higher chromium and lower carbon than the common cutlery-steel analysis. The results in Table 45 show that, in quenched and tempered specimens, strength and hardness were increased and elongation was decreased by increasing the manganese.

These steels do not develop the same hardness as the 0.3 per cent carbon, 13 per cent chromium cutlery steels. Monypenny(191) showed that manganese up to 2 per cent produces no important increase in the hardness of quenched standard cutlery steels. Unpublished data indicate that with more than 3 per cent manganese, machining, even in the annealed condition, is difficult and that corrosion resistance is decreased. On the

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* U. S. Patent 1,333,151, issued in 1920.

TABLE 45.—MECHANICAL PROPERTIES OF 16 TO 17 PER CENT CHROMIUM STEELS CONTAINING 1 TO 3 PER CENT MANGANESE

Composition, per cent				Oil quenched after holding 10 min. at		Brinell hardness	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Modulus of elasticity, million lb./sq. in.
C	Si	Cr	Mn	°C.	°F.						
0.20	0.30	16.17	1.06	925	1695	387					
				950	1740	364					
				975	1785	418					
				1000	1830	430					
				950*	1740*	357	189,200	88,750	50,000	10	32.8
0.20	0.30	15.74	2.49	925	1695	387					
				950	1740	444					
				975	1785	460					
				1000	1830	477					
				950*	1740*	418	208,500	94,500	61,000	7	33.0
0.18	0.30	17.04	1.98	925	1695	302					
				950	1740	321					
				975	1785	321					
				1000	1830	332					
				950*	1740*	321	151,600	81,100	50,300	..	29.4
0.18	0.30	16.97	2.78	925	1695	321					
				950	1740	332					
				975	1785	340					
				1000	1830	340					
				950*	1740*	332	168,200	90,500	46,500		

* Also tempered 3 hr. at 450°C. (840°F.) and air cooled.

other hand, it has been found that manganese up to 2 per cent improves hot working.

81. Effect of Small Amounts of Nickel.—Cutlery steels usually contain small percentages of nickel introduced accidentally with the scrap charged; but small quantities are also added intentionally in many instances. Nickel, in quantities insufficient to retain appreciable amounts of austenite, lowers the temperatures of transformations, particularly on cooling. It increases the hardening capacity of the steels and, to some extent, retards tempering after hardening. The effect of small amounts of nickel on the hardenability of medium-carbon 11 per cent chromium steels, as determined by Monypenny,(191) is shown in

Fig. 40. It is evident that nickel has no appreciable effect after hardening at 900°C. (1650°F.) followed by tempering up to 550°C. (1020°F.). If higher tempering temperatures are used, however, the presence of nickel increases the hardness for a given tempering treatment. The results obtained on steels 2 and 5, which, except for their nickel content, are of almost identical analysis, are especially illustrative. After tempering at 750 to 775°C. (1380 to 1425°F.), the steel with 0.6 per cent nickel had a Brinell hardness of 215, equivalent to a tensile strength of 106,000 lb. per sq. in., while the steel with 1.6 per cent nickel had a Brinell hardness of 340 and showed minimum hardness after tempering at 720 to 740°C. (1330 to 1365°F.), with a Brinell number of 244, equivalent to a tensile strength of 120,000 lb. per sq. in.

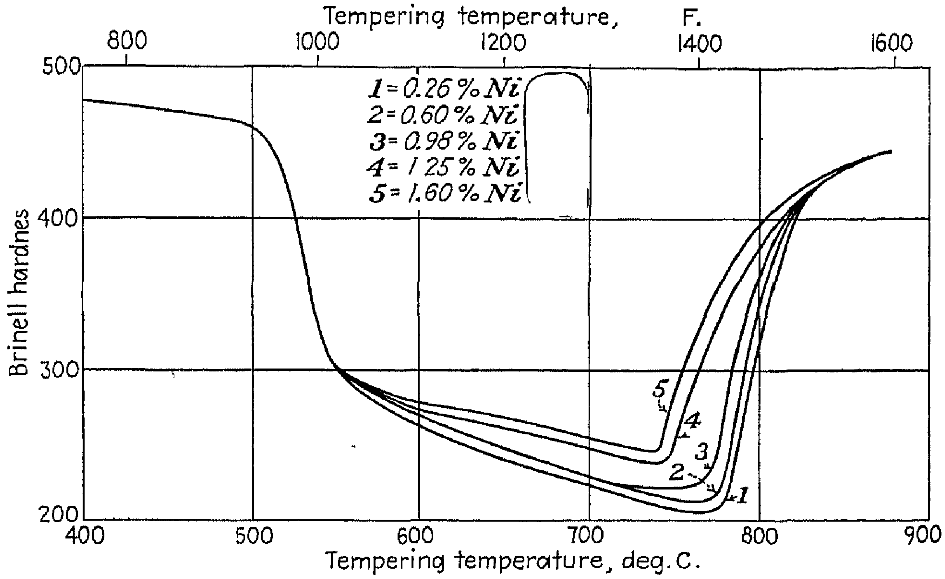

FIG. 40.—Effect of nickel on the resistance to tempering hardened steel containing 0.34 to 0.40 per cent carbon and 11.00 to 11.30 per cent chromium. (*Monypenny.*(191))

The influence of nickel in intensifying the air-hardening capacity of the same steels is shown in Table 46. In these tests the steels were heated to 900°C. (1650°F.) and, after soaking for 30 min., were transferred to furnaces at 700, 650, and 600°C. (1290, 1200, and 1110°F.); they were air cooled approximately to the temperature of the second furnace before transfer. The

TABLE 46.—INFLUENCE OF NICKEL ON THE AIR-HARDENING CAPACITY OF 11 PER CENT CHROMIUM STEELS CONTAINING 0.34 TO 0.40 PER CENT CARBON*

Steel No.	Nickel, per cent	Initial temperature		Time in second furnace, hr.	Brinell hardness of water-quenched samples after holding in second furnace at		
		°C.	°F.		700°C. (1290°F.)	650°C. (1200°F.)	600°C. (1110°F.)
1	0.26	900	1650	0.5	183	228	228
				1	179	228	228
				2	179	228	228
5	1.60	900	1650	0.5	444	340	340
				1	387	255	269
				2	332	228	228
1	0.26	1060	1940	1	196	217	217
				2	192	217	217
				4	192	212	217
				8	183	202	217
5	1.60	1060	1940	1	578	321	269
				2	495	277	255
				4	460	241	217
				8	351	223	217

*Monypenny (191)

samples were held at these temperatures for various periods and then quenched in water; thereafter their Brinell hardness was measured. A series of similar experiments was performed using a higher initial temperature, *viz.*, 1060°C. (1940°F.). The results showed that, whereas the 0.26 per cent nickel steel was readily softened after holding at any of the temperatures investigated, the 1.6 per cent nickel steel required a more prolonged soaking for softening. The Ar_1 temperature of the higher nickel steel is probably lower than 700°C. (1290°F.) even on slow cooling.

The data of Table 47 bring out the marked effect of nickel in intensifying the hardening capacity of 15 to 16 per cent chromium steels with 0.10 to 0.20 per cent carbon. It is shown that a tensile strength of at least 190,000 lb. per sq. in., a yield strength of at least 150,000 lb. per sq. in., and a minimum proportional limit of 75,000 lb. per sq. in. with an elongation of not less than 6 per cent can be obtained by adding slightly over 1 per cent nickel to these steels. These properties are obtained by hardening and tempering at 450°C. (840°F.). Incidentally, these steels were appreciably more corrosion resistant after hardening and tempering than 13 per cent chromium steels.

TABLE 47.—MECHANICAL PROPERTIES OF 16-1 STEELS OIL QUENCHED FROM 975°C. (1785°F.) AND TEMPERED AS SHOWN

Composition, per cent			Tempering			Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Brinell hardness	Modulus of elasticity, million lb./sq. in.
			Temperature		Time, hr.						
C	Ni	Cr	°C.	°F.							
0 17	1 29	15 64*	450	840	3	202,500	177,500	134,400	9	387	30 6
			500	930	1	184,000	157,000	116,200	15	332	31.7
			550	1020	0.5	164,000	140,000	95,000	13	321	
			650	1200	0.5	141,000	121,000	77,500	16	277	
			750	1380	8	114,000	75,000	45,000	23	207	28.0
0 11	1 15	16 55	450	840	3	174,000	145,000	89,500	16	364	
			500	930	1	195,000	155,000	....	18	351	
			550	1020	0.5	146,500	112,000		18	302	
			650	1200	0.5	111,500	88,000	....	21	228	
			750	1380	0.5	105,000	72,000	.	26	212	

* Tensile samples of this steel taken from ¼-in. plate. Samples from the other steel, taken from 1-in. rounds, were 0 505 in in diameter

The 17 to 18 per cent chromium, 2 per cent nickel steels are well known in England. Monypenny(191) reported that, because of their nickel content, they begin to harden when air cooled or quenched from temperatures above 700°C. (1290°F.), but that apart from this they respond to tempering in a manner similar to 12 to 14 per cent chromium steels. Some of his data, showing the effect of increasing carbon on the mechanical properties of these steels, are given in Table 48. According to the same investigator, the modulus of elasticity of these steels is similar to that of other hardenable steels. Owing to their combination of strength and resistance to corrosion, they are used extensively in the construction of seaplanes and flying boats.

TABLE 48.—THE EFFECT OF CARBON ON THE MECHANICAL PROPERTIES OF 17 TO 18 PER CENT CHROMIUM, 2 PER CENT NICKEL STEELS, AIR COOLED FROM 950°C. (1740°F.) AND WATER QUENCHED FROM 650°C. (1200°F.)*

Composition, per cent			Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation, in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness
C	Ni	Cr						
0.11	2.18	18.00	110,500	80,800	27.50	62.2	87 83 88	241
0.16	2.30	17.20	110,000	86,800	24.00	61.5	68 78 68	248
0.21	2.46	17.60	122,100	88,000	21.00	53.4	50 60 56	269
0.27	2.20	17.90	133,500	102,000	20.00	55.8	46 42 47	277
0.35	2.01	17.40	151,000	137,900	17.00	47.2	20 20 18	302

* Monypenny.(191)

Thus, the action of small percentages of nickel is to increase the ease with which the steels may be hardened and to produce full hardening of higher chromium analyses. This permits excellent mechanical properties to be obtained in a steel that is more resistant to corrosion than the standard 12 to 14 per cent chromium steels.

82. Effect of Molybdenum.—Until recently, molybdenum additions were not considered for general use in stainless steels of this category, although as early as 1910 Borchers and Monnartz claimed* that molybdenum improves the resistance of such steels to chemical attack. Oertel and Würth(93) investigated cutlery-type steels containing about 0.3 per cent carbon, 14 per cent chromium, and 0.3 to 4 per cent molybdenum. They showed that molybdenum additions of 1 to 3 per cent raised the temperature of the Ac_1 transformation and reduced air hardening. They also found that, to harden fully, the steels containing molybdenum should be heated at 1000 to 1050°C. (1830 to 1920°F.) or slightly higher temperatures. Monypenny's(191) data, reproduced in Fig. 41, confirm this for steels containing 2 per cent molybdenum.

Oertel and Würth(93) and Monypenny(191) agreed that molybdenum improves the resistance of these steels to weak solutions of hydrochloric, sulphuric, acetic, and nitric acids. The former

* German Patent 246,015, issued in 1913.

also reported that it improved resistance to sea water, and the latter noted a definite improvement in resistance to weak solutions of citric, tartaric, and other organic acids. As a result, up to 2 per cent molybdenum has been added to certain cutlery steels to eliminate rusting of the cutting edge of knives. A modification of this steel including 0.75 per cent molybdenum is now popular for special cutlery where the combination is claimed to give excellent retention of cutting edge. The molybdenum addition does not change the hardening practice but gives greater leeway in tempering.

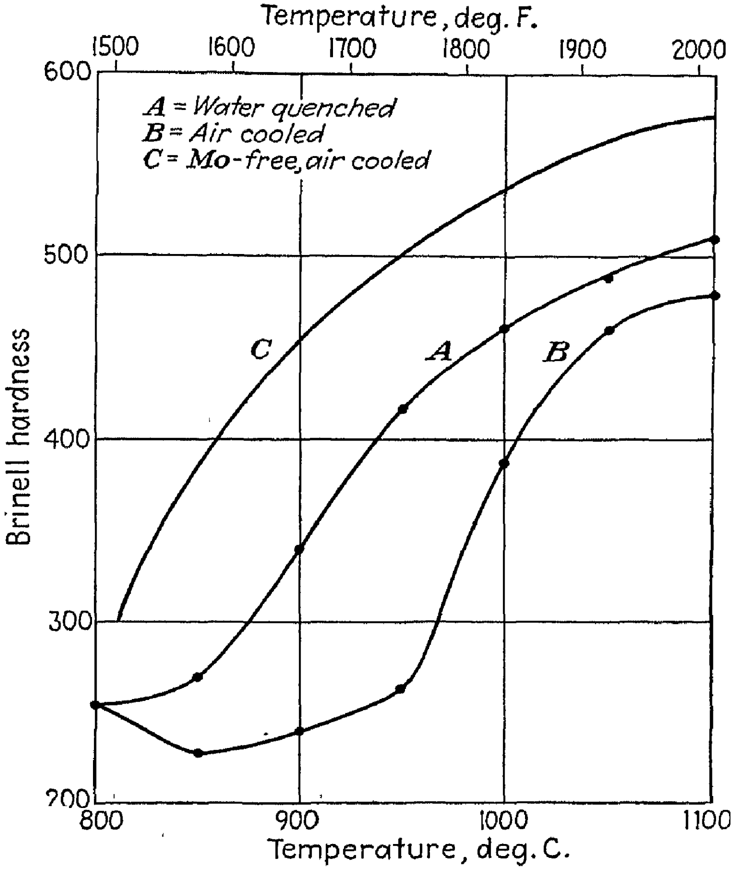

FIG. 41.—Effect of quenching temperature on the Brinell hardness of steel containing 0.24 per cent carbon, 12.8 per cent chromium, and 2 28 per cent molybdenum as compared with a molybdenum-free steel of similar carbon and chromium contents (*Monypenny.*[191])

83. Effect of Tungsten.—Monypenny(101) stated that although one might expect a small addition of tungsten to these steels to increase their hardening capacity, 1.4 per cent tungsten in a 12 per cent chromium steel produced no noticeable effect. He gave the data of Fig. 42 and added that, when fully tempered, the tungsten-bearing steel was distinctly harder than a similar stainless steel without tungsten. However, unlike molybdenum, tungsten does not increase the resistance of cutlery steels to attack by acetic, hydrochloric, sulphuric, and other acids and even decreases resistance to nitric acid.

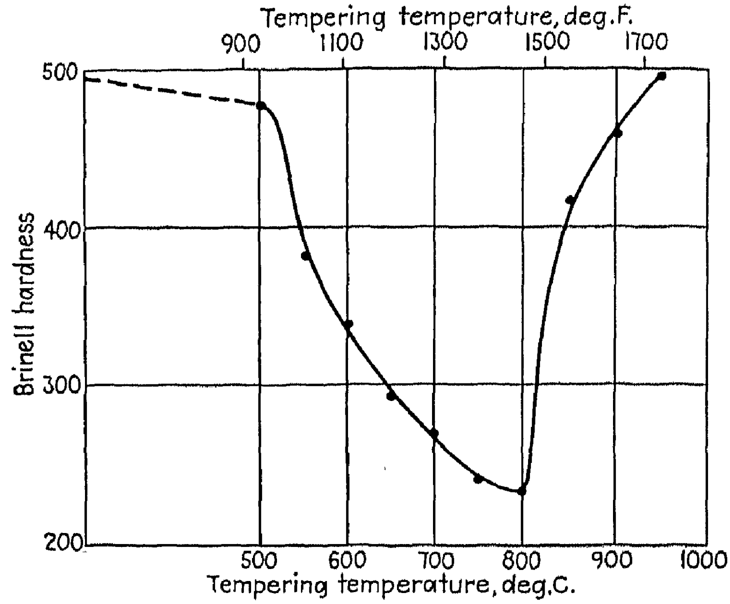

FIG. 42.—Effect of tempering on the hardness of steel containing 0.32 per cent carbon, 11.6 per cent chromium, and 1.40 per cent tungsten, air cooled from 1000°C. (1830°F.). Specimens were water quenched from the tempering temperature. (*Monypenny.*(101))

84. Effect of Copper.—Copper is not generally added to stainless steels of the cutlery type, although it tends to increase their corrosion resistance to certain media and their hardening capacity. Saklatwalla(55) claimed that copper additions are effective in such media as 5 per cent sulphuric acid, 5 per cent hydrochloric acid, mine water, sulphur dioxide water, vinegar, and lemon juice. He stated that the effective copper content depends on the chromium content, and that, generally, it does not exceed 1.5 per cent. It is most beneficial in steels containing less than 0.15 per cent carbon. Monypenny(191) reported that 1.2 per cent copper slightly increases the hardness of high-chromium steels, acting similarly to small percentages of nickel. On the other hand, he found the effect of copper different from that of nickel in that large copper additions did not render the steels fully austenitic. In this connection it is significant that the percentage of copper soluble in solid stainless steel is limited to a few per cent.

85. Effect of Titanium.—Titanium has been publicized mostly as a "carbon neutralizer" for stainless steels. The effect of larger additions was investigated by Comstock and Clark(448) who tested four steels containing 0.2 to 0.3 per cent carbon, about 17.5 per cent chromium, and up to 2 per cent titanium. Creep tests showed about 0.25 per cent titanium to be the most effective amount. This amount was also sufficient to increase resistance to oxidation at 870 and 980°C. (1600 and 1800°F.). Data are subjoined:

Titanium, per cent	Average weight gain in 1000 hr., g. per sq. in.
0	0.0593
0.25	0.0035
1.11	0.0094
1.97	0.0121

86. Applications.—Soon after Brearley showed that steels containing about 0.3 per cent carbon and 13 per cent chromium were suitable for cutlery, other investigators were quick to point out that the steels could be used in a great variety of applications in view of the combination of good mechanical properties and resistance to corrosion. Early in the history of stainless steels, Hadfield,(11) Aitchison,(15,24) Marble,(20) Parmiter,(53) Hatfield,(60) Handforth,(226) and others found that the stainless cutlery steels were suited for valves, valve stems, valve seats, ball bearings, turbine plates, pump parts, and many similar applications. This material was found to be useful also in hot-type extrusion dies, punches, molds for die casting, turbine blades, evaporating pans, rollers for ball bearings, and instruments for surgery, dentistry, in optical work, and the machine shop. Calipers and squares are typical of the last-named group.

Hultgren(45) reported that the cutlery-type stainless steels are not strong enough for use as ball bearings and that the deformation limits of these steels are considerably below those of the usual 1 per cent carbon steels containing 1.5 per cent chromium. The deformation limit has since been increased by increasing the carbon content; this is discussed in a later chapter. On the other hand, a steel of similar chromium content but lower carbon has supplanted cutlery steels for turbine blades. Chromium steels of other types are now being used instead of cutlery steels in valves for internal-combustion engines.

Although these stainless steels have found wide use as cutlery, they have not been applied as metal-cutting tools and only to a minor degree as cutting tools for wood and other relatively soft substances, where hardness at high temperature is not important. They do not approach the standard high-speed steels in retention of red hardness.

F. AUTHORS' SUMMARY

1. Of the medium-carbon 10 to 18 per cent chromium steels, those containing about 0.3 per cent carbon and 13 per cent chromium, or 0.7 to 1 per cent carbon and 17 per cent chromium are the most widely used for cutlery and allied purposes. Both steels possess their most useful properties in the hardened, tempered, and polished state; in this condition, the 17 per cent chromium steel has the greater hardness, wear resistance, and corrosion resistance.

2. The melting practice for these steels differs only in detail from that previously described for high-chromium steels, but all manufacturing steps from this point on are characterized by the need for additional precaution, owing to air hardening. Some of these difficulties can be avoided by care in heating and cooling. Temperatures recommended for two kinds of cutlery steels are summarized in Table 49.

3. After hardening, tempering, and polishing, the steels have high corrosion resistance in tap water, steam, fruit and meat juices, food acids and salts, ammonia, alkali solutions, lubricating oils, and greases. They are also fairly resistant to atmospheric corrosion, especially indoors. Out of doors, the steels frequently acquire a dark brown coating, which usually may be rubbed off leaving the surface beneath practically unimpaired. In industrial atmospheres, however, pitting of the surface may be serious under some conditions. Attack by

TABLE 49.—RECOMMENDED TEMPERATURES FOR THE WORKING AND HEAT TREATMENT OF 13 TO 17 PER CENT CHROMIUM STEELS

Operation	Temperature		Hardness	
	°C.	°F.	Brinell	Rockwell *C*
Composition range: 0.30 to 0.40% C, 0.30 to 0.50% Mn, 0.20 to 0.40% Si, and 13 to 14% Cr*				
Preheating	785 to 815	1450 to 1500		
Forging	925 to 1095	1700 to 2000		
Annealing for softness	860 to 885	1575 to 1625	165	
Annealing for machining	760 to 785	1400 to 1450	220	
Hardening	970 to 1010	1775 to 1850	550	56
Tempering	175 to 480	350 to 900	...	56 to 51
Composition range: 0.65 to 0.75% C, 0.40 to 0.60% Mn, 0 30 to 0.50% Si, and 16 to 17% Cr*				
Preheating	785 to 815	1450 to 1500		
Forging	925 to 1095	1700 to 2000		
Annealing for softness	885 to 915	1625 to 1675	200	
Annealing for machining	760 to 785	1400 to 1450	230	
Hardening	995 to 1050	1825 to 1925	600	60
Tempering	150 to 425	300 to 800	...	60 to 54

* Sulphur and phosphorus 0.03 per cent maximum.

hydrochloric, sulphuric, and sulphurous acids or chloride solutions is serious.

4. A wide range of properties is obtainable by tempering at different temperatures and by varying the chromium and carbon contents. As the steels are air hardening, they should be cooled slowly after fabricating operations at elevated temperatures, and if it is necessary to cool in air, they should be tempered to relieve strains. This is especially true for steels that are welded, riveted hot, or soldered. When fully annealed, the steels are readily machinable.

5. When more than 1 per cent silicon is present in cutlery steels, they become more difficult to hot work and fabricate. If the silicon content is increased to 3 per cent, they become brittle and practically non-hardenable. Silicon additions of this order increase the resistance to scaling and to corrosion in certain

media, but in other media, particularly nitric acid, silicon lowers corrosion resistance.

6. Increasing the manganese content of cutlery steels to 1 or 2 per cent intensifies their hardening capacity and facilitates hot working. If the manganese content is increased to 6 per cent or more, the steels become largely austenitic. (These steels are discussed in Chapter XIV.)

7. Nickel additions of 0.5 to 2 per cent intensify the hardening capacity of the steels more than the same amount of manganese. This element is employed to impart satisfactory hardening properties to steels containing less carbon and somewhat more chromium than those of the usual cutlery type. While nickel has not been added to steels intended for cutlery, it has been employed to obtain high-strength steels of the 18 per cent chromium, 2 per cent nickel, and 16 per cent chromium, 1 per cent nickel types. These steels contain less than 0.20 per cent carbon and are more resistant to corrosion than cutlery steels with higher carbon content. They are used primarily for structural applications.

8. Additions of small percentages of molybdenum or tungsten raise the temperature to which cutlery steels must be heated for hardening. Molybdenum also increases corrosion resistance to certain media. About 2 per cent molybdenum is frequently added to eliminate the slight rusting that may occur in certain organic reagents on the cutting edge of stainless-steel knives. A popular grade of cutlery steel contains 0.75 per cent molybdenum.

9. Surprisingly few changes have been made in the composition of the cutlery steels since they were first produced by Brearley in 1914. Although there has been a pronounced trend toward higher chromium and higher carbon, together with improved mill practice in handling such materials, a great tonnage of the original specification is still being manufactured. Modification of the steels by alloying elements in small percentages is practiced to some extent.

CHAPTER VI

HIGH-CARBON STEELS CONTAINING 10 TO 18 PER CENT CHROMIUM

Die Steels—Valve Steels—Authors' Summary

High-carbon high-chromium steels, *i.e.*, alloys containing from 1 to 2.5 per cent carbon and usually about 12 per cent chromium, are characterized by their ability to develop great resistance to wear. These so-called "die steels" are used in such applications as burnishing tools and rolls, broaches, brick-mold liners, clay-pulverizing blades, blanking dies, cold-extrusion dies, deep-drawing dies, wire-drawing dies, forming tools and rolls, gages, and many others. Various grades are marketed to meet demands of specific applications; *e.g.*, if the greatest possible resistance to impact is necessary, the lower carbon grades are ordinarily specified. Further, vanadium or molybdenum, or both, may be added, usually in amounts not exceeding 1 per cent. Still another grade contains several per cent cobalt.

The history of high-carbon high-chromium steels begins in 1892, for it was then that Hadfield(1) reported an extensive investigation of alloys containing 1.25 to 2.15 per cent carbon and 11 to 17 per cent chromium. They could be forged with difficulty or not at all and were otherwise thought to be unpromising. Later workers developed satisfactory hot-working procedures.

The idea of using high-carbon high-chromium steels for tools is probably ascribable to P. R. Kuehnrich, of England, according to statements of Cox (in discussion of a paper by Wills(412)) and of Tlach.* After experience with steel containing about 3.5 per cent chromium, dating from 1895, Kuehnrich began experimenting with higher chromium steels in 1903. The composition finally selected for tools was 1.4 to 2.5 per cent carbon and about 15 per cent chromium. According to Cox, two American engineers who were in Paris during this time learned of the "remarkable steel high in chromium," and when they returned to the United States research was begun (1908) at the Midvale Steel Company which resulted in the Furness-Patch patent* covering steel containing 1 to 2 per cent carbon and 15 to 20 per cent chromium.

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* Victor Tlach, private communication.

Up to 1 per cent nickel was often added to these early steels because of its "favorable influence on the malleability." Further work, seeking a substitute for tungsten high-speed steel during the war of 1914 to 1918, led to the discovery of a modification containing cobalt. (Currently this grade contains about 1.4 per cent carbon, 13 per cent chromium, 3 per cent cobalt, 0.5 per cent nickel, and 0.6 per cent molybdenum.) This was the first of the twentieth century air-hardening steels to achieve great commercial success; the first heat in America was made in 1916.

A. DIE STEELS

It appears that most of the high-carbon high-chromium steels for dies now marketed contain either no other special elements or relatively small amounts of molybdenum or vanadium, or both. The reason for the replacement of the modification containing cobalt is probably that improved technique of manufacturing permitted satisfactory results with the less expensive materials.

Little on these steels appeared in the technical literature until recently. Until the comprehensive papers by Gill(113) and Wills(412) were published in 1929 and 1935 respectively, almost the only sources of information were patent claims and advertisements. Exceptions were the contributions of Oertel(75) and of Schmidt and Jungwirth,(202) but they are not very illuminating today.

87. Melting and Pouring.—Information in addition to that summarized in Chapters II and III was given by Wills.(412) High-carbon high-chromium steels can be melted in the crucible or in the electric furnace; at present, the latter, with a basic hearth, is usual. A typical charge consists of about 30 per cent high-carbon high-chromium steel scrap, the remainder being high-grade steel scrap containing low sulphur and phosphorus, in the form of heavy plate or punchings. When melting is complete, it is usually found that carbon and chromium have dropped to 75 and 80 per cent of their initial amounts respectively. The heat is slagged off and then carburized with crushed electrodes. The bath is then covered with a deoxidizing slag of lime, fluorspar, and coke. When the slag is white and after increasing the temperature, ferrochromium is added—in several batches to prevent excessive chilling of the bath. If the final alloy is to contain other elements, they may be added shortly before the heat is poured, at a temperature about the same as that used for high-speed steel. The grade of high-carbon high-chromium steel containing about 1 per cent vanadium is more viscous than the others, and all are susceptible to piping and must be poured slowly. The usual ingot sizes are 8 in. square (700 lb.) and 12 in. square (1500 lb.).

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* U. S. Patent 1,206,902, dated Dec. 5, 1916.

88. Hot Working.—The high-carbon high-chromium steels are relatively hard at high temperatures and must be heated and forged with care. The relation between carbon and chromium contents is important; if the chromium exceeds 20 per cent, and if the carbon is high enough for the steel to have the hardness required for dies, hot working is impracticable. For steels containing the usual amount of chromium (10.5 to 12 per cent) the upper limit for carbon is about 2.6 per cent if the material is to be hot worked successfully. The minimum carbon content is about 1 per cent.

The Crucible Steel Company of America(519) recommends the following procedure for hot working:

> Beginning with a low fire, bring the temperature up very gradually to about 1095°C. (2000°F.) and discontinue forging before the temperature falls below 900°C. (1650°F.). The forging should be reheated if it cannot be finished at a single heating. . . . After forging and before the work has become entirely cool, it should be reheated to . . . between 955 and 980°C. (1750 and 1800°F.), followed by slow cooling in still air. This will relieve forging stresses.

The temperatures recommended by Wills(412) are somewhat different, as will appear from his schedule: The ingots or billets are soaked at about 760°C. (1400°F.) for several hours, then the temperature is gradually increased to about 1040°C. (1900°F.). A temperature of 1065°C. (1950°F.) should not be exceeded. (This limiting temperature is 30°C. (50°F.) lower than that of the foregoing quotation; further, according to Rapatz,(54) a brittle constituent appears at temperatures exceeding 1100°C. (2010°F.). This constituent, discussed elsewhere,* causes the metal to rupture in hot working.) The preheating time for 8-in. square ingots is about 16 hr.; that for 12-in. ingots is about 24 hr. The 8-in. ingots are hammered to 4-in. square billets with two reheatings; the minimum forging temperature is about 845 to 870°C. (1550 to 1600°F.). These temperatures are also lower than that proposed by the Crucible Steel Company of America, but they are higher than that quoted in Chapter III, page 43, for steels including those of lower carbon content.

It is not practicable to reduce ingots by rolling; however, after a preliminary reduction by hammering, which increases ductility by breaking down the carbide network and the cellular ingot structure, sections of useful size can be rolled without difficulty. After forging or rolling, the steel is cooled in still air. To relieve forging stresses, the Crucible Steel Company of America recommends immediate reheating to 955 to 980°C. (1750 to 1800°F.) followed by cooling in still air.

89. Annealing.—It is regular practice to anneal high-carbon high-chromium steels. According to Wills,(412) they are brought to a temperature of 870 to 900°C. (1600 to 1650°F.) in 6 to 8 hr., soaked 8 to 12 hr., then cooled over a period of 24 to 36 hr. The practice of the Crucible Steel Company of America is to pack the steel in some inert material in boxes or pipes, heat slowly to 900°C. (1650°F.), soak 1 hr., cool the furnace to 790°C. (1450°F.), soak 3 to 4 hr., cool at a rate of about 10°C. (20°F.) per hr. to about 650°C. (1200°F.), then "cool naturally" in the furnace. These treatments are intended to enable the user to machine the steels satisfactorily.

90. Effect of Annealing on Castings.—Cast steel containing 1.47 per cent carbon and 11.81 per cent chromium was annealed at various temperatures and for various lengths of time by Gross(493) to determine the effect on microstructure. It was found that such treatment resulted in precipitation of carbide and that, depending on the extent of precipitation, the matrix, upon subsequent air cooling, became martensitic, pearlitic, or of mixed structure. The amount of precipitated carbide depended upon temperature and time of annealing. Further, there were three distinct temperature ranges, *viz.*, above 850°C. (1560°F.), which resulted in a hard (martensitic to troostitic) matrix; between 850 and 600°C. (1560 and 1110°F.), which resulted in a machinable structure ("pearlitic"); and between 600 and 400°C. (1110 and 750°F.), which also resulted in a martensitic structure. Lower temperatures had no effect.

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* See p. 118.

Steels modified by the addition of tungsten, nickel, and manganese were tested also; tungsten increased carbide precipitation and hardening, whereas nickel and manganese had the opposite effect.

91. Heat Treatment.—Heat treaters of high-carbon high-chromium steels differ in their practices, but there are certain generalities. These materials have relatively low thermal conductivity and, in consequence, absorb heat relatively slowly. The carbides go into solution slowly; consequently, extra time must be allowed at the temperature of quenching if maximum hardness and wear resistance are to be developed. It is usual to preheat the steels at a temperature somewhat lower than that of quenching; it is also usual to protect the steel by a packing material such as charcoal, active or spent carburizing material, or cast-iron chips. A carburized case can be obtained by the use of active packing material.

According to Wills,(412) an atmosphere adjusted to hold scaling at a minimum is necessary if an open-fire furnace is used for hardening. In other electric and fuel-fired furnaces, scaling can be delayed by placing charcoal on the furnace bottom and by restricting the influx of air. In recent years furnaces with controlled atmospheres have become available; these save much of the time required in pack hardening.

The quenching temperature for maximum hardness depends somewhat on composition; in general, it may be stated that the greater the carbon content the lower is the permissible quenching temperature. This is in agreement with the temperatures recommended by several authorities, collected in Table 50. Other information given is preheating temperature, quenching medium, and tempering temperature. It is to be seen that there is considerable spread among the favorite preheating temperatures; this indicates lack of rigid requirements. So far as quenching temperatures are concerned, those shown are in reasonable agreement for comparable steels. Further, these temperatures are lower than that—about 1040°C. (1900°F.), according to

Wills(412)—at which grain growth is appreciable and distortion is excessive. The steels are air hardened as well as oil hardened, although the higher carbon grades require oil quenching for maximum hardness. Prompt tempering is recommended, usually in the range of 205 to 315°C. (400 to 600°F.), although higher temperatures are used for special requirements.

92. Dimensional Changes upon Heat Treatment.—Tool steels, including the high-alloy grades, undergo dimensional change upon

TABLE 50.—RECOMMENDED HEAT-TREATING TEMPERATURES FOR HIGH-CARBON HIGH-CHROMIUM STEELS

Authority	Steel	Composition, per cent					Preheating temperature		Quenching temperature		Quenching medium	Tempering temperature	
		C	Cr	Mo	V	Co	°C.	°F.	°C.	°F.		°C.	°F.
Crucible Steel Company(510)	*H.Y.C.C.*	2.25	12.0	...	0.25	..	705 to 760	1300 to 1400	955 to 995	1750 to 1825	Oil	205 to 315	400 to 600
	AIRDI	2.25	12 0	1.0	0.25	.	705 to 760	1300 to 1400	995 to 1025	1825 to 1875	Air or oil	205 to 315	400 to 600
	C.C.A.	1 50	12.0	0.8	0.25	...	705 to 760	1300 to 1400	980 to 1010	1800 to 1850	Air or oil	205 to 315	400 to 600
	La Belle 24	1.10	12 0	1.0	0.25	..	705 to 760	1300 to 1400	1010 to 1040	1850 to 1900	Air or oil	205 to 315	400 to 600
Wills(412)	1	2 40	11 5	....	....	..	......	....	900 to 955	1650 to 1750	Oil	205 to 315	400 to 600
	2	2.10	12.0	....	1 0	.	..	....	955 to 1010	1750 to 1850	Oil	205 to 315	400 to 600
	3	1.55	12.0	0.8	0 25	..	595	1100	955 to 1010	1750 to 1850	Air or oil	205 to 315	400 to 600
Gill(113)	*A*	2.38	12.5	....	....	..	...	.	925 to 980	1700 to 1800			
	B	2.12	13.2	....	0.8		...	....	955 to 1010	1750 to 1850			
	C	1.38	12.2	0.5	....	3 5	..	....	955 to 1010	1750 to 1850			
	D	2.17	13.4	....	....	.	.	....	955 to 1010	1750 to 1850			
	E	1 60	17.0	....	...	..	....	.....	1040 to 1095	1900 to 2000			
	H	2.19	12.0	....	0.7	0 7	.....	....	955 to 1010	1750 to 1850			
"Metals Handbook"(516)	12	2 10	12.0	....	....	.	815	1500	970 to 995	1775 to 1825	Oil	205 to 540	400 to 1000
	10	2 10	12.0	....	1.0	...	815	1500	970 to 995	1775 to 1825	Oil	205 to 540	400 to 1000
	13	1 50	12.0	0.75	....	.	815	1500	980 to 1025	1800 to 1875	Air	205 to 540	400 to 1000
									925 to 980	1700 to 1800	Oil	205 to 540	400 to 1000

quenching, tempering, and aging; this is of importance to the maker of precision gages; consequently, the matter has been investigated in detail. Results on steel containing about 1.2 per cent carbon and 18 per cent chromium were reported by French(25) and by Scott,(77) but this grade has not the hardenability of the 12 per cent chromium steel. Several of Scott's observations are of interest, however, *viz.*: (1) Upon tempering, the initial contraction was greater after water quenching than after oil quenching and also after using a high quenching temperature as compared with a low quenching temperature; (2) the final contraction was little affected by these factors; (3) all quenched but untempered steels contracted, the rate being much greater at 100°C. (210°F.) than at atmospheric temperature. After 6 months at atmospheric temperature, the contraction was about the same as after 1 hr. at 100°C. (210°F.).

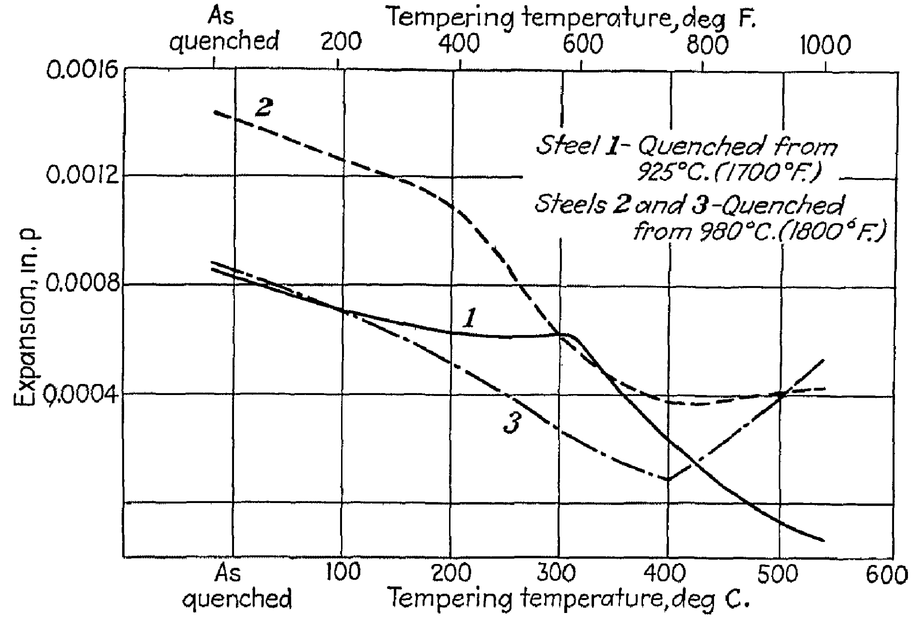


FIG 43.—Effect of tempering on the expansion of high-carbon chromium die steels. See Table 50 for composition. (*Wills.*(412))

Dimensional changes upon tempering of three standard grades of high-carbon high-chromium steels were reported in considerable detail by Wills.(412) Approximate compositions are given in Table 50, page 160. In the form of cylinders with parallel ends, specimens were measured before and after quenching, and after tempering. The results shown in Fig. 43 are for cumulative tempering of 1 hr. at each temperature. Other tests were made on steels 2 and 3 to determine dimensional changes after various heat treatments. Results showed that distortion was relatively low after air cooling from 980 to 1040°C. (1800 to 1900°F.), the treatment producing maximum hardness; the average length change was 0.0009 in. per in. The average for steel 2 was 0.00152 in. per in. after quenching in oil from 955 to 1040°C. (1750 to 1900°F.), the treatment for maximum hardness for this alloy. After tempering 2 hr. at 205°C. (400°F.) to produce a Rockwell *C* hardness of 62 to 64, the average expansion of steel 3 was 0.00052 in. per in., as compared with 0.0010 in. per in. for steel 2. Expansion became less as the tempering temperature was increased to that at which secondary hardening occurred; *i.e.*, in the neighborhood of 400 to 425°C. (750 to 800°F.).

All in all, the high-carbon high-chromium steels are usually said to have "good non-deforming properties."

93. Effect of Heat Treatment on Mechanical Properties.—The usual way of investigating the effect of heat treatment on high-carbon high-chromium steels has been to measure hardness. Of the published data, those of Bain,(44) Gill,(113) and Wills(412) are extensive. Bain's steels contained 2.22 per cent carbon and 10.56 per cent chromium, and 1.70 per cent carbon and 15.65 per cent chromium. They were oil quenched from temperatures ranging from 870 to 1205°C. (1600 to 2200°F.); this established the fact that maximum hardness was developed in the first steel by quenching from 980°C. (1800°F.) and in the second by quenching from 1040°C. (1900°F.).

Extensive tests on steels of composition given in Table 50, page 160, were reported by Gill.(113) Specimens, in the form of ¾-in. cubes, were annealed fully at 885°C. (1625°F.) before being heated for oil quenching. The steels were brought to temperature in 20 to 30 min. at a rate as uniform as possible and held at temperature for 15 min., with the exception of steel *E* (containing 17 per cent chromium) which was held 35 min. Results of hardness tests are shown in Fig. 44. The lowest quenching temperature for maximum hardness was obtained for steel *A* (about 2.4 per cent carbon and 12.5 per cent chromium) and the highest for steel *E*; that for the others was about the same

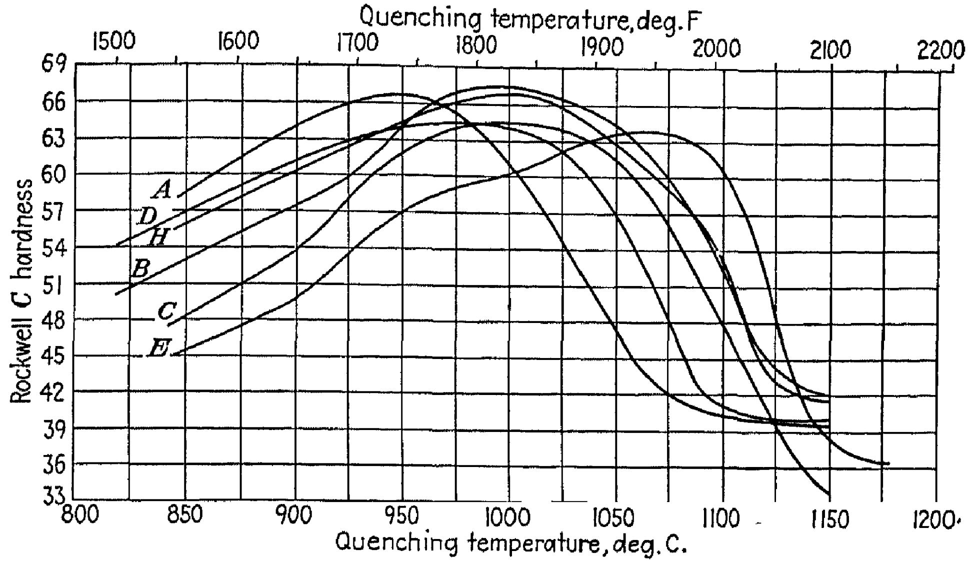


FIG. 44.—Effect of quenching temperature on the hardness of high-carbon chromium die steels. See Table 50 for composition. (*Gill.*[113])

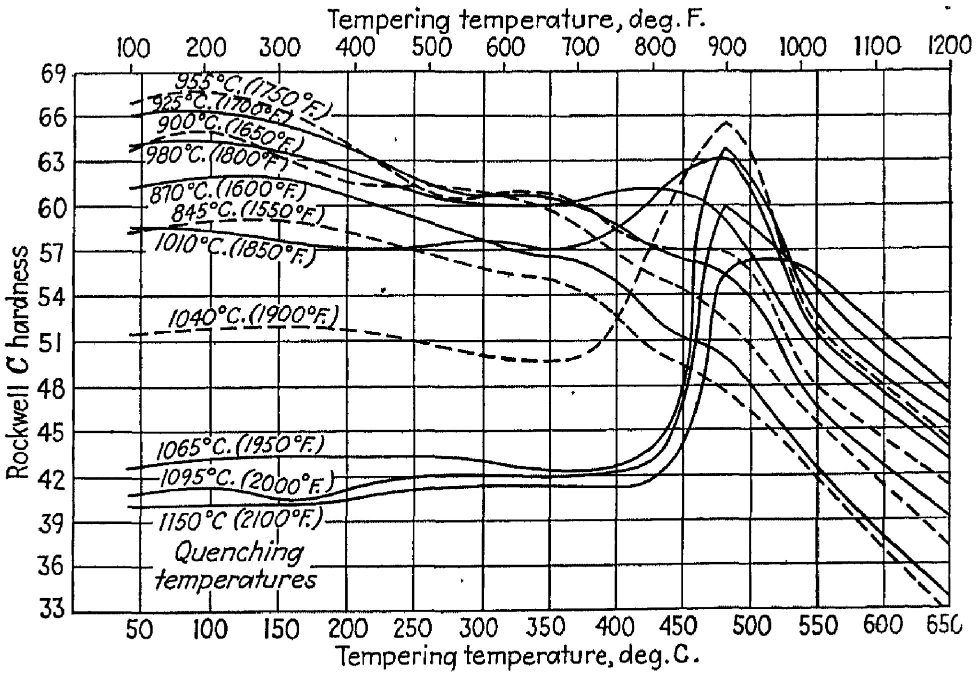


FIG. 45.—Effect of tempering on the hardness of quenched die steel containing 2.38 per cent carbon and 12.5 per cent chromium. (*Gill* [113])

in all instances; *i.e.*, about 980 to 1010°C. (1800 to 1850°F.). For tempering tests, Gill's specimens were brought to temperatures ranging from 150 to 650°C. (300 to 1200°F.) in about 45 min., held at temperature for 30 min., then air cooled. Results for steels *A* and *C* are given in Figs. 45 and 46.

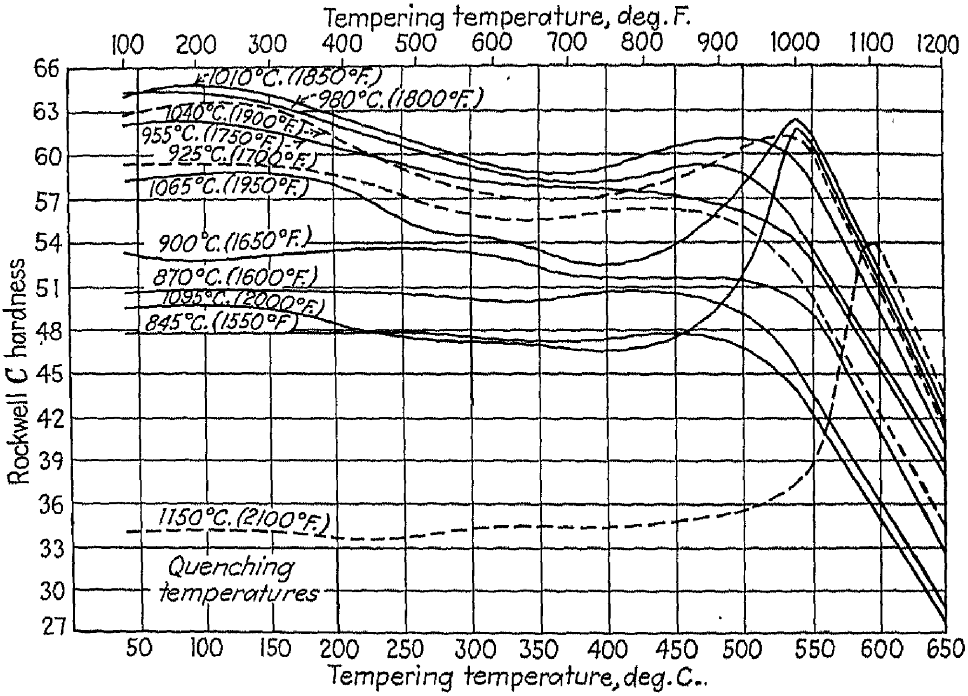


FIG. 46.—Effect of tempering on the hardness of quenched die steel containing 1.38 per cent carbon, 12.2 per cent chromium, 3.5 per cent cobalt, and 0.5 per cent molybdenum. (*Gill.*(113))

Gill's findings were substantiated by data obtained by Wills(412) on three grades of steel of composition given in Table 51. Other data given by Wills were on the effect of tempering temperature on the average resistance to impact and on compressive strength. The impact data are reproduced in Fig. 47; it is clear that resistance to impact and sensitivity to tempering temperatures are decreased by increased carbon content. Compressive strengths are given in Table 51.

The variation of hardness and of resistance to impact with quenching temperature of a steel containing 1.18 per cent carbon, 18 per cent chromium, and 1.2 per cent silicon was reported

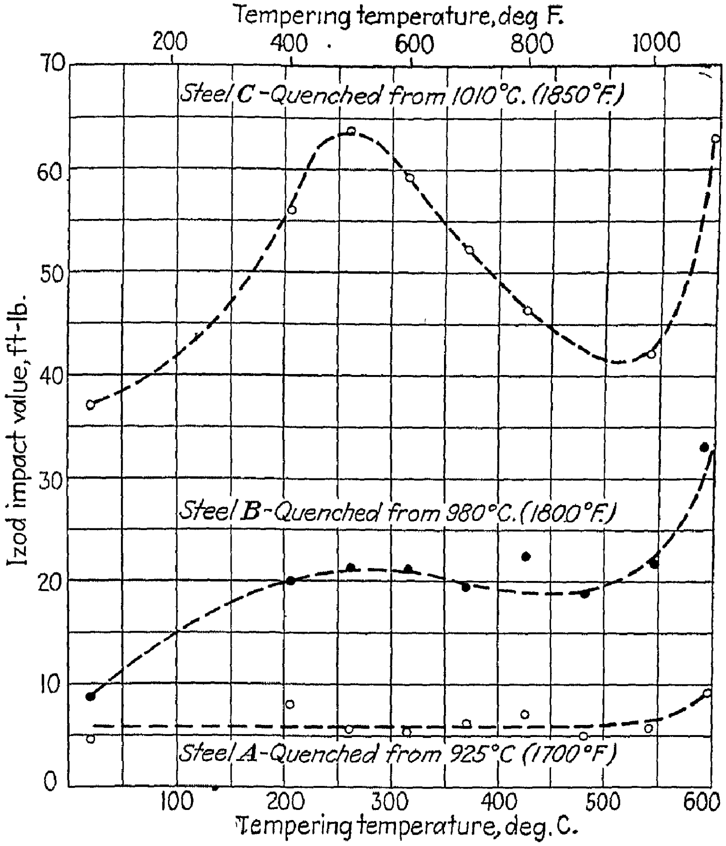


Fig. 47.—Effect of tempering on the impact resistance of quenched high-carbon chromium die steels. See Table 51 for composition. (*Wills.*[412])

Table 51.—Effect of Tempering Temperatures on the Compressive Strength of Three High-carbon High-chromium Steels*

Mark	Composition, per cent				Oil quenched from		Compressive strength, lb./sq. in. after tempering at		
	C	Cr	Mo	V	°C.	°F.	205°C. (400°F.)	315°C. (600°F.)	455°C. (850°F.)
A	2.40	11.5	. . .	. .	925	1700	438,500	396,600	302,100
B	2.10	12.0	. .	1.0	995	1825	425,500	389,300	350,400
C	1.55	12.0	0.8	0.25	995	1825	403,600	364,800	329,000

* Wills.[412]

by Sisco.(107) The resulting curve for hardness versus quenching temperature is similar to those shown here.

94. Other Properties.—The variation of specific volume with quenching temperature of a steel containing 2.19 per cent carbon, 12.01 per cent chromium, 0.72 per cent vanadium, and 0.66 per cent cobalt is shown in Fig. 48; these data were computed from densities given by Gill.(113) Comparison of this curve with that for the variation of hardness with quenching temperature (steel *H*, Fig. 44) shows their similarity; this is reasonable, because the maximum of the hardness curve must correspond with the greatest retention of martensite, indicated by the maximum of the specific-volume curve, since the specific volume of martensite is greater than that of either ferrite or austenite. The value for the annealed steel indicates that the specific volume of the 12 per cent chromium steel is about 0.001 cu. cm. per g. greater than that of a carbon steel of the same carbon content.

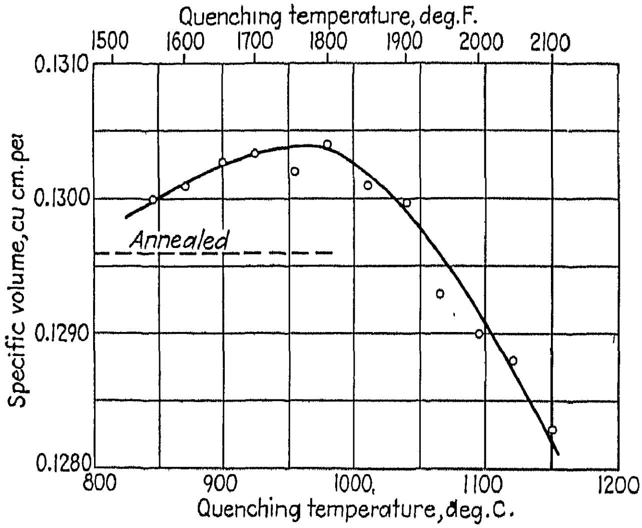


FIG. 48.—Effect of quenching temperature on the specific volume of a steel containing 2.19 per cent carbon, 12.01 per cent chromium, 0.72 per cent vanadium, and 0.66 per cent cobalt. (*Plotted from data of Gill.*(113))

Coefficients of thermal expansion of a steel containing 1.78 per cent carbon and 18.28 per cent chromium, reported by Cox, are given in Table 52; it is to be seen that they are not very different from those of carbon steel.

TABLE 52.—COEFFICIENTS OF THERMAL EXPANSION OF A STEEL CONTAINING 1.78 PER CENT CARBON AND 18.28 PER CENT CHROMIUM*

Heat treatment	Coefficient of expansion × 10^6			
	Temperature range		Per °C.	Per °F.
	°C.	°F.		
Annealed at 885°C. (1625°F.)... ...	30 to 205	85 to 400	9.0	5.0
	30 to 425	85 to 800	10.4	5.8
	30 to 650	85 to 1200	10.8	6.0
	30 to 785	85 to 1450	11.7	6.5
	205 to 425	400 to 800	11.5	6.4
	425 to 650	800 to 1200	12.8	7.1
	650 to 785	1200 to 1450	13.7	7.6
Oil quenched from 1010°C. (1850°F.).	−8 to 22	18 to 72	12.0	6.66
Tempered at 425°C. (800°F.).......	−8 to 95	18 to 206	12.4	6.86

* Cox, in discussion of paper by Wills.(412)

Data on thermal conductivity, reported by Schmidt and Mann,(440) are given in Fig. 49. The decrease of conductivity with temperature shown for steel 8 is probably characteristic of the steels discussed in this chapter. The curve for steel 17,

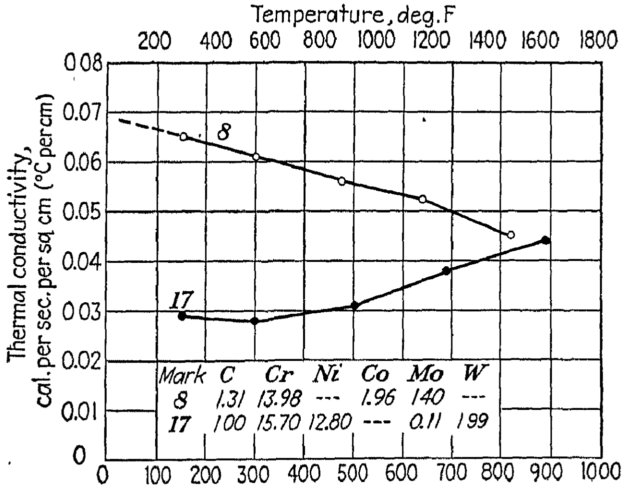


FIG. 49.—Thermal conductivity of some high-carbon chromium steels. (*Schmidt and Mann.*(440))

which contained a substantial proportion of nickel, exhibits the increase of conductivity with temperature characteristic of iron-chromium-nickel alloys.

95. Machining and Machinability.—As stated on page 156, high-carbon high-chromium steels in the form of the modification containing about 3 per cent cobalt attained some prominence during the World War as a possible "tungstenless" high-speed steel. It is now the consensus of authorities that cobalt steel is not a substitute for the tungsten and tungsten-molybdenum steels. As an example of tests of the chromium-cobalt steels, however, the report of Baxter, in discussion of a paper by Mathews,(13) may be cited. Favorable results were reported by Heyfets(320) for a steel containing 1.2 per cent carbon, 14.16 per cent chromium, and 0.55 per cent vanadium used as twist drills; but they should be verified before acceptance.

It is generally agreed that all grades of high-carbon high-chromium steel are machinable. Machinability is greatest, of course, after full annealing and decreases with increasing carbon.

96. Wear.—It is well known that laboratory wear tests are difficult to interpret in terms of service conditions. However, French and Herschman(83) devised an apparatus approximating such conditions for testing plug gages, made of various materials, against file-hard high-carbon steel, aluminum alloys, and a pearlitic cast iron. Chromium-plated and nitrided gages showed the least wear, but those made from high-carbon high-chromium steel, stellite, and high-speed steel showed fewer scratches.

The best evidence of the great wear resistance of hardened high-carbon high-chromium steels, however, is the fact that they are preferred for such applications as those enumerated on page 155.

97. Mechanical Properties at Elevated Temperatures.—There are few data on the properties of high-carbon high-chromium steels at elevated temperatures. Short-time tensile tests reported by Houdremont and Ehmcke(115) for two steels containing (*A*) 1.5 per cent carbon and 13.5 per cent chromium and (*B*) 1.2 per cent carbon, 13.1 per cent chromium, and 1.5 per cent tungsten are subjoined:

Temperature		Steel *A*		Steel *B*	
°C.	°F.	Tensile strength, lb./sq. in	Yield strength, lb./sq in	Tensile strength, lb /sq in.	Yield strength, lb./sq. in.
700	1290	21,800	17,100	22,800	15,600
800	1470	13,500	9,200	12,400	9,200
900	1650	11,200	8,500		

Similar results were obtained by Page and Partridge(154) for a steel containing 1.41 per cent carbon, 11.7 per cent chromium, 2.94 per cent cobalt, and 0.38 per cent molybdenum. According to Handforth,(226) the resistance to impact of this grade of steel becomes greater at elevated temperatures. Long exposure to elevated temperatures reduces impact resistance at room temperature but does not affect that at high temperature.

B. VALVE STEELS

Requirements for valves, formulated by experts after years of experience, include such matters as freedom from scaling at operating temperatures, hardness and strength at operating temperatures to avoid breakage and distortion, transformation temperature greater than 815 to 870°C. (1500 to 1600°F.) to prevent distortion and air hardening, and others. A variety of materials have been tried, and no single composition is universally accepted. However, chromium-silicon steels are popular for automobile-engine valves, and the steels used for aircraft-engine valves—a more severe service—invariably contain substantial percentages of chromium. The carbon content of valve steels is usually less than 1 per cent.

98. High-carbon High-chromium Valves.—According to Boegehold and Johnson,(173) chromium-cobalt steel containing 1.2 to 1.5 per cent carbon, 11.5 to 14 per cent chromium, 2.5 to 4 per cent cobalt, and 0.45 to 1 per cent molybdenum is harder than chromium-silicon steel and has been found to be "suitable for unlubricated valves and designs in which there is a side thrust causing rubbing of the stem against the guide." This material retains its hardness at operating temperatures and has great resistance to wear, as is stated elsewhere. It has the disadvantages, however, of low resistance to impact and sensitivity to small seams. Its resistance to oxidation is somewhat less than that of the chromium-silicon steels.

Others to discuss the chromium-cobalt steels, usually containing molybdenum, have been Johnson and Christiansen,(47) Ostroga,(94) French,(98) Hatfield,(101) Strauss,(163) Handforth,(226) and Musatti and Reggiori.(329) In these contributions there is ample confirmation of the aforementioned relatively low resistance to impact; the data given in Table 53 were obtained by Handforth.

TABLE 53.—EFFECT OF HEAT TREATMENT AND TEMPERATURE ON THE RESISTANCE TO IMPACT OF A CHROMIUM-SILICON AND A CHROMIUM-COBALT-MOLYBDENUM VALVE STEEL*

Composition, per cent					Heat treatment	Izod impact, ft-lb., at			
C	Si	Cr	Mo	Co		Room temperature	750 to 800°C. (1380 to 1470°F.)	800 to 850°C. (1470 to 1560°F.)	850 to 900°C. (1560 to 1650°F.)
0.39	3.35	8.75	....	....	Air quenched from 1000°C. (1830°F.). Tempered at 750°C. (1380°F.)	7 to 9	74	67	63
					1000 hr. at 750 to 800°C. (1380 to 1470°F.)	3	70		
					1000 hr. at 800 to 850°C. (1470 to 1560°F.)	2.5	..	68.5	
					1000 hr. at 850 to 900°C. (1560 to 1650°F.)	3	..	....	51
1.19	0 53	12.7	0.73	3.21	Air quenched from 950°C. (1740°F.). Tempered at 750°C. (1380°F.)	6 to 7	19	22	30
					1000 hr. at 750 to 800°C. (1380 to 1470°F.)	4.5	16		
					1000 hr. at 800 to 850°C. (1470 to 1560°F.)	4	..	26	
					1000 hr. at 850 to 900°C. (1560 to 1650°F.)	4	..	....	32

* Handforth.(226)

New problems confronted the maker of valves upon the introduction of fuel containing tetra-ethyl lead, because the products of its combustion are more corrosive than those of untreated gasoline. According to Handforth, the chromium-cobalt steels are relatively non-resistant to corrosion in the presence of decomposed tetraethyl lead. (Chromium-nickel steels are the most resistant of the valve steels now in use; this is discussed in detail in Chapter XII.) It does not seem possible to have a material that is desirable in all respects, consequently, selection of a valve steel involves judgment and compromise. A discussion of the corrosion resistance and the hot hardness of high-chromium valve steels is given on pages 389 to 400.

C. AUTHORS' SUMMARY

1. High-carbon high-chromium steels containing from 1 to 2.5 per cent carbon and about 12 per cent chromium have useful resistance to corrosion and wear and, in consequence, are widely used for dies, gages, and such articles.

2. As currently produced, high-chromium die steels often contain additions of molybdenum or vanadium, or both. Another grade, containing about 3 per cent cobalt, seems to be of decreasing importance.

3. High-carbon high-chromium steels must be heated and forged with care. The usual practice is to soak the ingots at an intermediate temperature before heating to the forging temperature. The maximum permissible forging temperature is 1050 to 1100°C. (1920 to 2010°F.).

4. It is the usual practice to anneal high-carbon high-chromium steels in order to enable the user to machine them satisfactorily. Heating to about 900°C. (1650°F.) followed by slow cooling is usual.

5. High-carbon high-chromium steels must be heat treated to develop their desirable properties of hardness and wear resistance. The pieces are packed in a protective material or are heated in a controlled atmosphere to prevent decarburization and scaling.

The quenching temperature for maximum hardness depends somewhat upon composition. In general, the greater the carbon content the lower is the permissible quenching temperature. Prompt tempering is advisable, usually in the range 205 to 315°C. (400 to 600°F.), although higher temperatures may be used for special requirements.

6. High-carbon high-chromium steels are relatively non-deforming during and after heat treatment.

7. High-carbon chromium-cobalt steels have some characteristics that have caused their trial as exhaust valves, but they are less resistant to the products of combustion of "doped" fuel than some other materials. Further, these steels are relatively brittle in impact and seem to be sensitive to such defects as small seams.

CHAPTER VII

PLAIN AND MODIFIED CHROMIUM STEELS CONTAINING 20 TO 35 PER CENT CHROMIUM

Manufacture and Fabrication—Physical Constants—Mechanical Properties—Corrosion and Oxidation Resistance—Modified 20 *to* 30 *Per Cent Chromium Steels—Authors' Summary*

The high-chromium steels containing more than 20 per cent chromium are a development of the past 25 years; according to MacQuigg,(380) castings of this material were used industrially in the United States as early as 1915, low-carbon plate and sheet were rolled by 1919, and tubes were pierced in 1923. There are few early published reports on these steels; Haynes(18) observed in 1920 that, during forging, high-chromium steels are freer from scaling than ordinary carbon steels, and in 1923 MacQuigg(187) reported a large amount of data. Becket's(108) early work on these steels showed that there was a marked increase in the oxidation resistance at 1000°C. (1830°F.) of low-carbon iron-chromium alloys as soon as a chromium content of 20 per cent was reached and exceeded. According to him, such alloys "excelled considerably even those of 18 or 19 per cent"; they exhibited negligible progressive oxidation after several weeks' exposure at 1095°C. (2000°F.), owing to the formation of a thin adherent layer of oxide, which was self-healing if ruptured, and which was impervious to oxidizing gases at elevated temperatures. Industrial development was rapid in the United States and abroad, especially when it was found that oxidation resistance was almost independent of the carbon content of the alloys. Thus, highly resistant steels of low carbon content could be made which were soft and easily worked both hot and cold, while unforgeable high-carbon alloys could be cast into hard, abrasion-resistant articles for use at elevated temperatures.

There is some confusion in terminology as applied to high-carbon high-chromium cast steels and high-chromium cast irons. In general, the former are melted in the electric furnace from steel scrap, and the chromium is added as the high-carbon ferroalloy; the high-chromium cast irons may be melted in the cupola, air furnace, or electric furnace, usually with cast iron as the raw material. However, differences in raw materials or melting procedure are not always evident in the published data, nor are investigators always careful in their use of the words "cast iron" or "steel." There is little doubt that the distinction between cast iron and steel as applied to these high-carbon alloys should be made, if possible, according to raw materials and method of manufacture, rather than according to any single element in the chemical analysis of the alloy. For purposes of ready classification and discussion in this monograph the method of manufacture has been used as a means of major division, but where there was any doubt the silicon content has been used as the dividing line; *i.e.*, those alloys containing less than 1 per cent silicon are treated in this chapter, and those containing more than 1 per cent silicon are discussed in Chapter VIII.

The industrial range for chromium in these oxidation-resistant materials is 23 to 35 per cent. Material that is to be hot or cold worked generally contains less than 0.3 per cent carbon; in the cast alloys, the carbon varies from less than 0.3 to 2 per cent or even more. Furman,(269) for example, discussed four classes of cast alloys containing: (1) less than 0.30 per cent carbon, (2) about 0.50 per cent carbon, (3) 1 to 1.5 per cent carbon, and (4) about 2.75 per cent carbon. Those of the first three classes contained less than 1 per cent silicon; the 2.75 per cent carbon alloy contained 3 per cent silicon and is clearly a cast iron. Furman recommended that for maximum corrosion resistance the carbon be not over one one-hundredth of the chromium content.

At room temperature, steels containing 25 to 30 per cent chromium and less than 0.70 per cent carbon consist of alpha iron and the carbide $(Cr,Fe)_4C$; they are not hardenable by heat treatment. The phase diagrams of the steels in this composition range are discussed in detail in Chapter III of the first volume of this monograph.

A. MANUFACTURE AND FABRICATION

In general, the melting practice for the 20 to 35 per cent chromium steels is the same as for the usual stainless grades described in Chapter II. The workability, either hot or cold, depends primarily on the carbon content; the steels containing less than about 0.35 per cent carbon are readily hot rolled, forged, or pressed. Higher carbon steels are difficult to hot work. According to Schmidt and Jungwirth,(202) it is impracticable to hot work the steels that contain more than 1 per cent carbon, especially with chromium near the upper limit.

99. Melting Practice.—The electric furnace is generally employed for melting. In the production of ingots to be forged and rolled, a basic lining is preferred, and two slags are used during melting and refining, whereas in most instances an acid lining and one slag are used for metal to be poured into castings. In a discussion of the production of low-carbon chromium steels containing up to 30 per cent chromium, Feild(356) pointed out that the procedure varies somewhat according to the required carbon content of the finished steel. When a steel of low carbon content is required, it is necessary to use the proper type of low-carbon steel scrap, which is remelted in a basic-lined furnace and treated with roll scale or iron ore to reduce the carbon content to about 0.04 per cent, after which the metal bath is cleaned as free as possible from the oxidizing slag. The melt is then covered with a finishing slag made of lime and fluorspar and treated from time to time with pulverized ferrosilicon and additional lime, if necessary, to maintain during the melting operation a slag of the disintegrating type.

After the slag is in shape and the steel is properly deoxidized with manganese and silicon, ferrochromium of the proper carbon content is added gradually to the melt through the slag. In view of the relatively large quantities of ferrochromium required, it is usually added in several batches. When the ferrochromium has been added to the bath and has been mixed thoroughly by stirring, the melt is sampled and the chromium content adjusted. The bath is finally brought to the proper temperature, after which it is deoxidized with manganese and silicon and tapped. Feild called this a conventional method, but cautioned that the exact practice employed by the different manufacturers of these steels varies in the methods of introducing ferrochromium and of final deoxidation.

He pointed out that in making low-carbon grades, the most important point is to prevent excessive carbon pickup, which can be done only by keeping carbonaceous products away from the molten steel. He also stated that there is less difficulty in melting the medium-carbon high-chromium steels containing about 0.40 per cent carbon, because a predetermined carbon pickup can be permitted. Ferrochromium with a somewhat higher carbon content can be employed in melting these steels, and a certain amount of pulverized coke instead of ferrosilicon can be used in shaping the finishing slag. In discussing the production of castings of the 20 to 35 per cent chromium steels, MacQuigg(187) noted that adding too much ferrochromium at one time may chill the bath, and that by adding it too slowly the viscosity of the slag may be decreased and the furnace walls and roof become overheated.

According to Pakulla and Rudnik,(331) the silica content of the slags used in melting these steels is between 20 and 30 per cent, and between 0.6 and 1 per cent chromium oxide is invariably present. This is enough to color the slag green and to give it a vitreous acid-like character, even though it shows the disintegrating characteristics of the white slag; this oxide content may interfere to a slight degree with complete deoxidation.

For the manufacture of castings containing 20 to 35 per cent chromium, the acid, rather than the basic, process is generally used. MacQuigg,(187) in comparing the two processes, noted that although acid practice produces a very liquid metal that usually gives a smooth and sound casting, there is danger of undue pickup of both carbon and silicon. Kerns,(72) who found the acid process as satisfactory as the basic, gave a description of the former for steel containing 0.4 to 0.6 per cent carbon, 0.6 to 0.8 per cent manganese, not over 0.5 per cent silicon, and 25 to 30 per cent chromium. The charge consisted of low-carbon scrap and ferrochromium containing 1 per cent carbon. One-third of the ferrochromium was added with the scrap and the rest at 2- or 3-min. intervals after the charge was melted and was hot enough. As much lime was added to the slag as was possible without affecting the acid lining. The color of the final slag is green or brownish green, and the loss in chromium is less than 1 per cent. According to Kerns, no deoxidizing agent other than the usual ferromanganese is necessary since enough silicon is reduced from the slag by the arc, or is present in the ferrochromium, to deoxidize the melt. It is difficult to judge accurately the temperature of the metal in the furnace.

100. Castings.—A large part of the tonnage of the 20 to 35 per cent chromium steels is poured into castings. According to MacQuigg,(187) the same difficulties met with in the foundry practice for carbon and low-alloy steels are also encountered for these special alloys, but in greatly intensified form. They have low thermal conductivity and relatively high shrinkage, which may result in localized strains and actual cracks. Simonds,(127) in discussing the practice for steels containing 28 per cent chromium and less than 0.5 per cent carbon, stated that green sand molds faced with graphite may be employed, but gates must be larger and many more risers must be used than are necessary for carbon and low-alloy steels. Pattern makers' shrinkage is ¼ in. per ft. according to Simonds(127) and MacQuigg(40,187); the latter stated in this connection:

> With higher carbon alloys this heavy shrinkage is intensified due to the wide range between the liquidus and solidus which results in an unusually long period between incipient and complete freezing.

Despite difficulties in casting these alloys, MacQuigg(187) found the 25 to 30 per cent chromium iron a more satisfactory alloy to work with from the foundryman's standpoint than the 16 to 18 per cent chromium alloys.

The low-carbon high-chromium steels are sluggish in the molten condition and must, therefore, be poured relatively hot to fill the mold completely. Hot pouring, however, as emphasized by Furman,(269) results in large grain size with accompanying brittleness unless, of course, the section is small enough so that the metal freezes quickly. Furman noted that although it is sometimes possible to refine the grain by thermal treatment (this depends on the carbon), in general the grain size of the casting cannot be changed. Because of this,

> it is necessary to pour on the cold side to ensure as small a grain as possible and yet have the metal hot enough to flow. This means a narrow temperature range for pouring.

Naturally the design of the casting, the pouring temperature, and other factors will affect the quality to a marked extent; thus, castings of identical composition may vary widely in their characteristics.

Adcock,(65) Franks,(267) and recently Colbeck and Garner(518) studied the effects of nitrogen, in the form of chromium nitride, on high-chromium steels. Adcock concluded that nitrogen acts similarly to carbon, but Franks and Colbeck and Garner observed that nitrogen reduced the grain size and increased the ductility, toughness, and strength of 20 to 30 per cent chromium steels. The use of high-nitrogen ferrochromium containing about 70 per cent chromium and 0.7 per cent nitrogen was recommended to obtain this result. Franks's data showed that the finished high-chromium steel should contain not less than approximately one hundred times as much chromium as nitrogen. This was confirmed by Colbeck and Garner, who found that gassy ingots resulted if the nitrogen exceeded the ratio recommended by Franks. The latter's findings on the effect of nitrogen on grain size have also been confirmed by Furman(269) (under commercial conditions) and by Norwood.(330)

101. Hot and Cold Working.—Few specific data on the mechanical working of high-chromium steels have been published. MacQuigg(40,187) stated that the steels in this class roll or forge about as well as medium-carbon steel, provided the carbon is below 0.5 per cent. They are, however, considerably stiffer than carbon and low-alloy steels so that more power is necessary to work them; in addition, hot-working temperatures must be more closely controlled. MacQuigg(40) recommended 950 to 1050°C. (1740 to 1925°F.) as finishing temperatures, depending on the operation, with 800 to 850°C. (1470 to 1560°F.) as the lower permissible range. However, initial temperatures as high as 1150°C. (2100°F.) are used in forging and rolling ingots. Trouble in hot working increases with the carbon content; the ease of deformation is much more closely related to the amount of carbon than to the chromium content; with 2.5 per cent carbon the metal is extremely difficult to forge or roll.

Spenlé(443) determined the effect of chromium and other alloying elements on the reduction by hot rolling. He used 15 carbon and alloy steels in the form of 50-mm. (2-in.) squares which were given one pass under identical conditions, *i.e.*, the surface of the rolls, their speed, and the rolling temperature—1100°C. (2010°F.)—were held constant. The pressure in rolling was plotted against the "reduction coefficient," which was defined as the increase in width divided by the decrease in height. As shown in Table 54, 16 and 30 per cent chromium steels were stiffer than plain low-carbon, low-chromium, and 18 per cent chromium, 8 per cent nickel steels.

TABLE 54.—REDUCTION COEFFICIENTS OF CARBON AND CHROMIUM STEELS IN ROLLING 1 PASS AT 1100°C. (2010°F.)*

Mark	Composition, per cent			Reduction coefficient for a pressure in rolling of			
	C	Cr	Ni	10%	20%	30%	40%
Carbon	0.10			0.23	0.40	0.58	
Low-Cr	0.45	1.5		0.35	0.48	0.63	0.77
16% Cr .	0.10	16		0.40	0.58	0.74	0.86
30% Cr. .	0.25	30		0.32	0.52	0.70	0.83
18-8. . .		18		0.23	0.40	0.60	0.73

* Spenlé.(448)

The correlation between the reduction coefficient, as determined by Spenlé, and the elevated-temperature strength of high-chromium steels and of 18-8 is not good. It is shown in a later chapter that the 18-8 material is much stronger at high temperatures than high-chromium steels containing no nickel; this would not be expected from the data of Table 54.

Franks's(360) investigation on nitrogen-containing high-chromium steels indicates that these are easier to roll and forge than comparable steels containing no nitrogen. This was confirmed by Wright and Newell in discussion. Newell also noted an improvement in cold-forming properties but cautioned against nitrogen contents above 0.3 per cent as having the opposite effect on 25 per cent chromium steels. Colbeck and Garner,(518) who melted their nitrogen-containing steels in small lots (12.5-lb. ingots), were able to forge them from 2.5-in. squares to ⅞-in. rounds, provided the forging temperature was 1000°C. (1830°F.) or higher. Even if the ingots were sound, they cracked badly if forged at lower temperatures.

Johnson and Sergeson(230) found that 25 per cent chromium steels containing no added nitrogen were difficult to cold roll in thicknesses below 0.035 in. The trouble was due to the steel's marking the rolls. Colbeck and Garner tried cold rolling a water-quenched low-carbon 25 per cent chromium steel containing 0.25 per cent nitrogen and found that a ⅛-in. forged plate could be readily reduced to strip 0.006 in. thick, the thinnest material possible on the small hand mill they had available. Three intermediate annealings at 1150°C. (2100°F.) were necessary.

102. Machinability and Wear Resistance.—Owing to the inherent hardness of the carbides present in the 20 to 35 per cent chromium steels, these materials are much more difficult to machine than ordinary low-carbon steels. MacQuigg,(187) however, stated that in general the machinability depends more upon the structure than upon the chromium content. If annealed properly, a steel containing 25 to 30 per cent chromium and 2 to 2.75 per cent carbon can be machined. This is confirmed by Houdremont and Wasmuht,(182) who stated that with low speeds and heavy cuts, castings containing 34 per cent chromium and 1.1 to 2.3 per cent carbon (with 1 to 1.5 per cent silicon) can be machined with high-speed steel tools and that "in cases of particular difficulty, the use of the tungsten carbide type of tools has given satisfaction."

Apparently nitrogen improves the machinability of the low-carbon high-chromium steels, as Colbeck and Garner(518) found that

> the high-nitrogen steels show a marked improvement over the coarse-grained low-nitrogen steels, both in cutting speed and in finish. This characteristic . . . is of considerable value, particularly in the fabrication of small machined parts—the cutting of screw threads and similar operations.

The hard complex carbides of iron and chromium in the high-carbon 20 to 35 per cent chromium steels are responsible for the high abrasion and wear resistance of these materials.(182,187) According to MacQuigg(40) (who gave no specific data), an alloy containing 2.7 per cent carbon and 26.4 per cent chromium, when used to grind zirkite or sintered magnesite, showed less wear than chilled cast iron and equaled high-manganese steel. An advantage of the high-carbon chromium steel is that it does not spall so readily as chilled cast iron.

In general, the wear resistance of iron-chromium alloys increases with the chromium content. Eilender, Oertel, and Schmalz(313) tested a series of alloys made from electrolytic iron and high-purity chromium, using the Spindel machine. A revolving disk of carbon steel containing 0.23 per cent carbon, 0.18 per cent silicon, and 0.34 per cent manganese was pressed against the specimen with a force of 8 kg. (17.6 lb.). The wear was expressed by measuring the area of the segment produced by the revolving disk on the iron-chromium alloys. Results were as follows:

Chromium, per cent	Area, sq. mm
0	140
5	85
10	55
15	40
20	35
22	33

103. Welding.—Little information is available on the welding of these high-chromium steels. According to Tangerman(164) and Miller,(190) gas welding the high-chromium steels containing less than 0.3 per cent carbon is difficult, especially for heavy gages; with the proper flux, however, it is possible to make satisfactory flange and butt welds. The flame must be kept neutral or slightly reducing, as an appreciable excess of acetylene results in the absorption of carbon by the weld. Grain growth occurs readily at welding temperature; the welds have ample strength but little or no ductility. High-carbon castings must be preheated before welding, and must be cooled slowly to prevent cracking; annealing after welding is recommended.

In a general discussion of the arc welding of high-chromium alloys, Hodge(368) pointed out that, although welds of low-carbon 25 to 35 per cent chromium steels are so brittle at room temperature that they will not withstand any appreciable impact or bending load, they are quite ductile at 260°C. (500°F.) or above so that "welded structures may be employed at elevated temperatures without cracking in service." He also found that welds in plates containing 0 10 per cent carbon and 26 per cent chromium, made with an electrode containing 0.25 per cent carbon and 28.76 per cent chromium, had an (unnotched-bar) impact value of 4 ft-lb. Using a welding rod of approximately the same carbon and chromium contents, but containing also 0.33 per cent nitrogen, raised the impact resistance of the weld somewhat; in both tests, however, elongation and reduction of area were zero.

Franks(360) determined the mechanical properties of welds in low-carbon 25 per cent chromium steels containing nitrogen, made with rods of the same composition as the plate metal. His results are shown in Table 55.

104. Heat Treatment.—The phase diagrams given in the first volume of this monograph (Chapter III) indicate that the structure of steels containing 25 to 35 per cent chromium and less than 0.5 per cent carbon cannot be changed by thermal treatment. Cold-worked low-carbon alloys may be annealed to soften them and to remove the effect of cold deformation, and castings of the same class are commonly annealed to remove strains. According to MacQuigg(40) and Furman,(269) the steels containing about 30 per cent chromium become embrittled when held in the temperature range 425 to 540°C. (800 to 1000°F.), so that slow cooling through this range should be avoided. The brittleness is only evident in tests made at room temperature (or below the temperature of boiling water), and the ductility can be restored if the material is reheated to 650°C. (1200°F.) or above and cooled rapidly. This brittleness is apparently closely allied in nature to the temper brittleness common to some tempered and slowly cooled low-alloy steels and to the drastic loss in impact resistance of cutlery steels tempered at 450 to 500°C. (840 to 930°F.), as found by Tour.(444) (This is illus-

TABLE 55.—MECHANICAL PROPERTIES OF WELDS MADE IN ANNEALED ¼-IN. PLATE OF HIGH-NITROGEN 25 PER CENT CHROMIUM STEELS*

Composition, per cent			Method of welding	Condition of weld	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 1 in., per cent
C	Cr	N					
0.17	24.19	0.24	Oxyacetylene	As welded	92,700	66,500	3
				Heat treated†	80,500	57,100	7
0.19	25.30	0.24	Arc	As welded	85,500	64,000	7
				Heat treated†	82,400	53,600	10

* Franks.(360)

† Heated at 875°C. (1605°F.) for 4 hr. and air cooled.

trated in Chapter V, page 123.) The temper brittleness—or 475°C. brittleness—of the 25 per cent chromium steels is discussed further in this chapter.

High-carbon castings are hard and practically unmachinable in the cast condition; according to Furman,(269) the Brinell number may be as high as 550. These steels can be softened for machining by annealing for long periods at 750 to 800°C. (1380 to 1470°F.), followed by slow cooling. If the 25 per cent chromium steel contains more than 0.7 per cent carbon, it can be hardened by heating to 850°C. (1560°F.) or above and quenching.(40) Higher carbon alloys—1.5 per cent or more—can be hardened by air cooling. For annealing the high-carbon alloys MacQuigg(40) recommended heating to 800°C. (1470°F.) and cooling slowly to 600°C. (1110°F.) followed by more rapid cooling.

B. PHYSICAL CONSTANTS

The general effects of chromium on the physical constants of low-carbon iron are discussed in the first volume of this monograph (Chapter V); the data given for low-carbon alloys in Chapter IV of the present volume include some of the constants for alloys containing more than 20 per cent chromium. It is only necessary, therefore, to collect in this chapter the values not already given, with special attention to alloys containing considerable carbon and more than 20 per cent chromium.

105. Density and Specific Volume.—As shown in Chapter IV, Fig. 20, the specific volume of the alloys of iron and chromium is practically a linear function of the chromium content for amounts between 20 and 35 per cent; the density decreases from 7.72 for 20 per cent chromium to 7.62 g. per cu. cm. for 35 per cent chromium. Low-carbon steels containing 25 to 30 per cent chromium are, therefore, about 5 per cent lighter than unalloyed low-carbon steel.(301)

Carbon apparently lowers the density; for a steel containing about 0.3 per cent carbon, not over 1 per cent silicon, and 25 to 30 per cent chromium, it is 7.54(506); and for an alloy containing 1.1 to 2.3 per cent carbon, 1.3 per cent silicon, and 34 per cent chromium, it is 7.43 g. per cu. cm.(182)

106. Thermal Conductivity and Thermal Expansion.—The thermal conductivity at 100°C. (210°F.) of low-carbon 25 to

30 per cent chromium steels is 42 per cent of that of an unalloyed low-carbon steel.(301) According to Shelton and Swanger,(294) it increases from 0.050 cal. per sec. per sq. cm. (°C. per cm.) at 100°C. (210°F.) to 0.058 at 500°C. (930°F.). This may be compared with a value of 0.065 at 500°C. (930°F.) for low-carbon 15 per cent chromium steel. The effect of increasing chromium on the thermal conductivity of iron is plotted in Chapter IV, Fig. 21. No data could be found on the high-carbon alloys, but it is probable that their conductivity is lower than that of a comparable material containing no chromium. One manufacturer(486) of the low-carbon 25 per cent chromium steel gives its thermal conductivity as 0.059 cal. per sec. per sq. cm. (°C. per cm.) between 20 and 100°C.

TABLE 56.—COEFFICIENTS OF THERMAL EXPANSION OF STEELS CONTAINING 34 PER CENT CHROMIUM*

Temperature range, °C.	Coefficient of thermal expansion × 10^6, per °C.	
	Steel *A* (1.1 per cent C)	Steel *B* (2.3 per cent C)
0 to 100	9.8	9.4
0 to 200	10.2	10.3
0 to 300	10.6	10.8
0 to 400	10.9	11.3
0 to 500	11.2	11.4
0 to 600	11.4	11.5
0 to 700	11.6	11.9
0 to 800	12.2	12.3
0 to 900	12.7	12.7
0 to 1000	13.1	13.0

* Houdremont and Wasmuht.(182)

Data for the coefficients of thermal expansion of low-carbon iron-chromium alloys containing up to 50 per cent chromium are also summarized in Chapter IV, where it is stated that the mean coefficient is not markedly different from that of alpha iron. Mean values for the temperature range 0 to 100°C. for steels containing approximately 30 per cent chromium, which indicate the effect of carbon, are as follows:

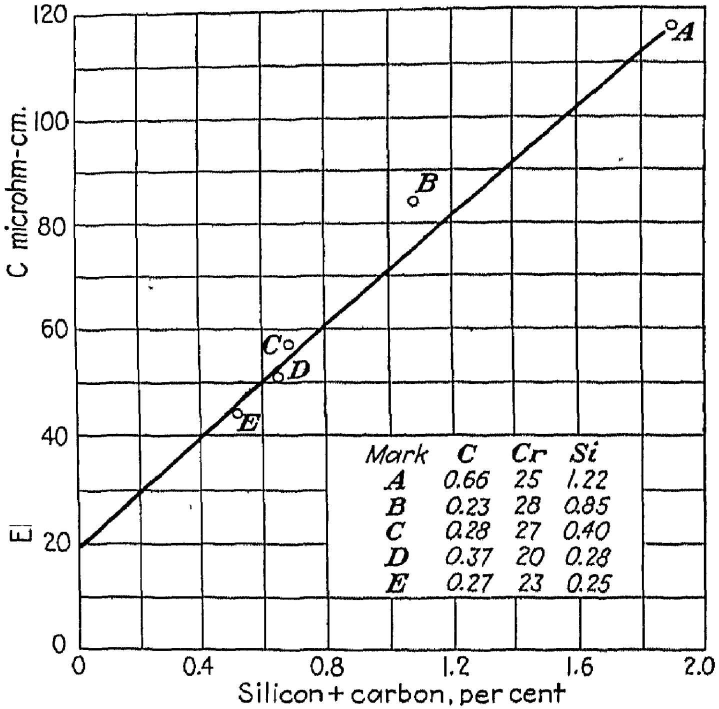
Carbon content, per cent	Mean coefficient of thermal expansion, × 10^6	Source
Under 0.10	10.6	United States Steel Corporation(301)
0.35	10.6	Rustless Iron and Steel Corporation(506)
1.1	9.8	Houdremont and Wasmuht(182)
2.3	9.4	Houdremont and Wasmuht(182)

The coefficients of thermal expansion, for various temperature ranges, of two high-carbon steels, as determined by Houdremont and Wasmuht(182) are given in Table 56. Steel *A* contained 33.6 per cent chromium, 1.3 per cent silicon, and 0.42 per cent manganese, and steel *B* contained 34.2 per cent chromium and about the same amounts of silicon and manganese.

107. Magnetic and Electric Properties.—The magnetic properties of low-carbon iron-chromium alloys are discussed in Chapter IV, page 96. In general, the ferromagnetism of such materials is roughly inversely proportional to their chromium content. Increased carbon content results in further decrease of magnetism; consequently, the magnetic properties as such of iron-chromium-carbon alloys are of little interest. However, the fact that the ferritic phase of all but the highest chromium alloys is ferromagnetic, whereas the austenitic phase is not, makes possible a simple test for the presence of ferrite. This is especially useful in the investigation of the effects of thermal and mechanical treatments on persistently austenitic alloys such as 18-8, a fact quickly recognized by a number of workers, among whom Mathews(61) and Strauss(95) may be cited.

Owing to the oxidation resistance of high-chromium steels, considerable attention has been paid to their electric resistance, to determine whether they are suitable for electric heating elements. According to Hunter and Jones,(32) steels containing about 22 per cent chromium have been used, but not extensively, as they are inferior to the standard nickel-chromium and iron-nickel-chromium alloys. In addition to Hunter and Jones, early investigators of the electric properties of alloys containing more than 20 per cent chromium were MacQuigg(40) and Mathews(61) in this country, Edwards and Norbury(16) in England, and Portevin,(5) Boudouard,(6) and Galibourg(58) in France.

Chromium increases the resistivity of low-carbon iron; in the high-chromium ranges the increase is linear from about 63 microhm-cm. for a rolled or annealed 18 per cent chromium alloy, to 73 microhm-cm. for an alloy containing 23 per cent chromium.(66) Work hardening increases the resistivity. Benedicks and Sundberg(66) found an increase of 3 to 4 microhm-cm.



Mark	C	Cr	Si
A	0.66	25	1.22
B	0.23	28	0.85
C	0.28	27	0.40
D	0.37	20	0.28
E	0.27	23	0.25

FIG. 50.—Electric resistance of commercial steels containing 20 to 27 per cent chromium. (*MacQuigg*.(187))

in low-carbon material and much more in medium- and high-carbon alloys; according to Portevin,(5) the increase upon quenching averaged 2 per cent for chromium percentages of 26 to 40 and a carbon content of 0.2 per cent. Mathews(61) determined the resistivity of a quenched steel containing 0.30 per cent carbon and 29.77 per cent chromium as 71.9 microhm-cm., as compared with 69.4 for the same material in the normalized condition.

Carbon has a marked effect on resistivity. In an investigation of a series of annealed steels containing up to 20 per cent chromium and variable carbon, Edwards and Norbury(16) found that chromium causes an increase of 3.75 microhm-cm. for each

1 per cent in excess of 4.3 times the carbon content. The effect of carbon plus silicon in steel containing 20 to 27 per cent chromium was determined by MacQuigg(187); his data are shown in Fig. 50. From this it is evident that 0.4 per cent carbon plus silicon increases the specific resistance by an approximately uniform amount of 40 microhm-cm. Figure 51 gives the electric resistance of commercial 23 to 30 per cent chromium steels as reported by a manufacturer.(486)

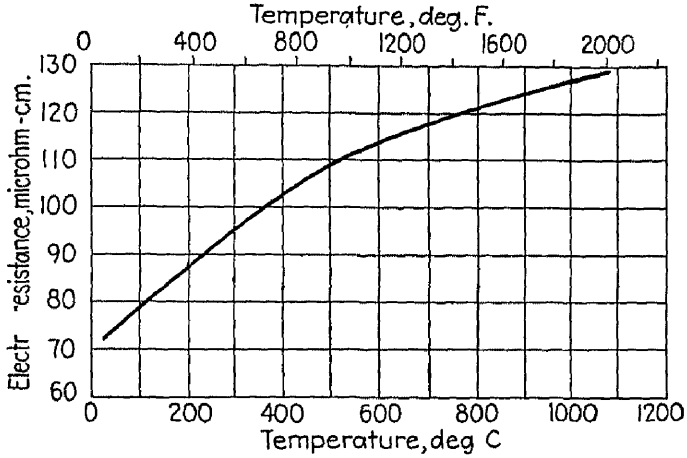


Fig. 51.—Electric resistance of commercial 23 to 30 per cent chromium steels. (*Allegheny Ludlum Steel Corporation.*(486))

The temperature coefficient of electric resistivity is high. An alloy containing 0.27 per cent carbon and 23.49 per cent chromium had a resistivity of 17.3 microhm-cm. at room temperature and 2.6 times this value at 1100°C. (2010°F.) according to measurements by MacQuigg(40) on 0.025-in. wire.

The effect of temperature on two resistance alloys was determined by Hunter and Jones.(32) The alloys used had the following composition:

Element	Percentage	
	Alloy *A*	Alloy *B*
Carbon .	0.18	0.65
Silicon .	1.67	1.24
Chromium	22.06	22.23
Nickel . . .	0.87	1.17

On the basis of a resistance of 100 at 20°C. (70°F.), resistance values at increasing temperatures were as follows:

Temperature		Alloy *A*	Alloy *B*
°C.	°F.		
20	70	100.0	100.0
300	570	112.9	113.2
400	750	117.5	117.4
500	930	122.5	123.5
600	1110	127.8	128.3
700	1290	131.6	132.2
800	1470	133.8	134.1
900	1650	135.7	135.5
1000	1830	137.5	136.5

The increase in resistivity with temperature, as determined by these investigators, is large, but not so large as that found by MacQuigg.(40)

The thermoelectric properties of chromium steels containing up to 30 per cent chromium and 0.1 to 0.8 per cent carbon were determined by Dupuy and Portevin,(9) who used two temperature ranges, −80 to 0°C. (−110 to 30°F.) and 0 to 100°C. (30 to 210°F.). With copper as the other element, the values between 0 and 15°C. (30 and 60°F.) were positive, but the plotted curve is not linear. According to Dupuy and Portevin, the curve is of a type characteristic of steels containing double carbides.

C. MECHANICAL PROPERTIES

At room temperature, chromium, at least up to 30 per cent, is soluble in alpha iron; consequently, as is characteristic of solid solutions in general, the strength and hardness of iron-chromium alloys are greater than the corresponding properties of pure iron. Pakulla and Oberhoffer,(62) Adcock,(168) and Eilender, Oertel, and Schmalz(313) determined the effect of increasing chromium on the hardness of iron; the hardness of an alloy containing 30 per cent chromium is about twice that of an alloy containing 5 per cent chromium.' The effect of increasing the chromium from 12 to 21 per cent on the tensile properties of annealed steels containing about 0.10 per cent carbon is shown in Chapter IV, Table 3.

The tensile strength of the 21 per cent chromium steel is about 30 per cent higher than that of the 12 per cent chromium alloy, the yield strength is 50 per cent higher, and the Brinell hardness about 16 per cent higher. Elongation and reduction of area are lower; the former by about 30 per cent, the latter by 15 per cent.

108. Room-temperature Mechanical Properties of Hot-worked Steels Containing 20 to 35 Per Cent Chromium.—According to a manufacturer's data sheet,(301) the range of tensile properties and hardness values for steels containing less than 0.1 per cent carbon, less than 0.5 per cent manganese and silicon, and 25 to 30 per cent chromium is as follows:

Property	Annealed	Cold worked
Tensile strength, lb. per sq. in	75,000 to 95,000	85,000 to 175,000
Yield strength, lb. per sq. in....	50,000 to 60,000	55,000 to 155,000
Elongation in 2 in , per cent.....	20 to 30	
Elongation in 10 in., per cent. ..	....	25 to 2
Reduction of area, per cent .	50 to 60	55 to 25
Brinell hardness.......... .. .	160 to 190	150 to 250

Actual properties for steel containing 0.09 per cent carbon, 0.29 per cent manganese, 0.12 per cent silicon, and 28.28 per cent chromium, furnace cooled from 855°C. (1575°F.), as determined by Saklatwalla and Demmler,(124) were as follows:

Tensile strength, lb. per sq. in..	85,000
Yield strength, lb. per sq. in	57,000
Elongation in 2 in., per cent	27
Reduction of area, per cent...... -	40
Brinell hardness............	194

Quenching in water from 995°C. (1825°F.) and tempering at 425°C. (800°F.) did not affect the hardness; similar quenching followed by tempering at 600°C. (1110°F.) lowered the hardness to 169 Brinell.

Results for several forged and heat-treated steels containing between 0.14 and 2.02 per cent carbon and 22 to 28 per cent chromium, obtained by MacQuigg,(380) are given in Table 57. Tensile strengths are between 75,000 and 110,000 lb. per sq. in.; elongation and reduction-of-area values are low, except for the alloys that were water quenched after 10 hr. at 850°C. (1560°F.).

TABLE 57.—MECHANICAL PROPERTIES OF FORGED AND HEAT-TREATED 20 TO 30 PER CENT CHROMIUM STEELS*

Composition, per cent				Heat treatment	Tensile strength, lb./sq. in.	Yield strength lb./sq.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	Si	Mn	Cr							
0.14	0.	50	26.28	Forged	89,000	62,000	9.0	11.0	170	2.0
				Water quenched after 10 hr. at 850°C. (1560°F.)	83,000	56,000	26.0	61.0	159	2.0
				Air cooled after 30 min. at 950°C (1740°F.)	66,000	49,000	5.0	6.0	137	
0.24	0.11	0.26	27.73	Water quenched after 10 hr. at 850°C. (1560°F.)	75,800	53,400	31.3	59.1	143	1.0
0.75	0.75		23.12	Cooled in 5 days to 20°C. (70°F.) after heating to 850°C (1560°F.)	95,800		11.0	11.8	223	
2.02	0.50		22.25	Cooled slowly to 600°C (1110°F.) after heating to 850°C. (1560°F.)	110,000	100,000	9.0	12.7		

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* MacQuigg.(380)

Rapid cooling from around 900°C. (1650°F.) is necessary to produce the maximum combination of strength and toughness by any practical treatment.

This conclusion is in line with unpublished work by Norwood, in which he heated samples of 25 per cent chromium-steel sheets at temperatures between 400 and 950°C. (750 and 1745°F.). The cooling rates were varied between slow furnace cooling and water quenching. He observed that with chromium contents of 20 per cent or more, holding of the steels in the temperature range 400 to 550°C. (750 to 1025°F.) caused brittleness, which could be removed by heating at temperatures above 600°C. (1110°F.), followed by rapid cooling. This temper brittleness was called "475°C. (890°F.) brittleness" by Norwood because the temperature was midway in the range 400 to 550°C. (750 to 1025°F.) The same investigation showed that maximum softness and ductility were produced in sheets of these steels by water quenching from about 900°C. (1650°F.). In discussing later the possible cause of this brittleness, MacQuigg(380) suggested that the phenomenon was akin to that common in 18-8, which has been explained by the rejection of carbides to the grain boundaries, but stated that experiments under way (in 1935)

> indicate that the two phenomena are symptoms of even more widely occurring alteration of solid solutions in general, and that carbon is merely one of the elements able to bring about the fundamental changes.

As noted on page 124, a similar brittleness was found by Tour in hardened chromium cutlery steels tempered at about 475°C. (890°F.). A further clue to the cause of the phenomenon is Becket's(488) report that the fracture of the 25 per cent chromium steels made brittle by holding at 475°C. (890°F.) is across the grains rather than at the grain boundaries.

Structural changes in the 20 to 35 per cent chromium steels—as in all chromium steels—are sluggish. Arness and Ostrofsky(213) subjected 1-in. square bars of three of these steels to long-time treatments. Compositions and the properties resulting from these treatments are given in Table 58. The extremely

TABLE 58.—EFFECT OF LONG-TIME TREATMENTS ON THE MECHANICAL PROPERTIES OF HIGH-CHROMIUM STEELS*

Composition, per cent					Heated 10 hr at		Cooled in	Tensile strength, lb./sq in.	Yield strength,† lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
C	Mn	Si	Cr	Ni	°C.	°F.						
0.08	0.37	0.51	21.80	0.19	790	1450	Water	74,000	42,500	34.0	64.7	170
					830	1525	Water	74,800	40,000	31.0	62.3	170
					870	1600	Water	71,800	41,300	35.0	64.7	170
					830	1525	Furnace	77,500	47,500	32.0	64.7	167
0.13	0.33	0.48	21.49	0.26	790	1450	Water	72,800	42,500	33.5	51.9	170
					830	1525	Water	74,000	42,500	32.5	54.7	170
					870	1600	Water	71,800	42,500	35.5	59.8	170
					830	1525	Furnace	77,700	50,000	30.5	58.6	163
0.21	0.41	1.05	26.45	0.20	790	1450‡	Water	77,000	52,500	26.0	57.3	170
					830	1525‡	Water	74,300	50,000	29.0	58.6	187
					870	1600‡	Water	68,800	53,800	3.0	1.9	170
					830	1525‡	Furnace	70,000	55,000	2.0	1.9	179

* Arness and Ostrofsky (213)

† For a set of 0.5 per cent.

‡ Held 15 hr.

low elongation and reduction-of-area values of the 0.21 per cent carbon, 26.45 per cent chromium steel after 15 hr. at 870°C. (1600°F.) when quenched in water, and at 830°C. (1525°F.) when cooled in the furnace, are noteworthy, especially when compared with MacQuigg's(380) data (Table 57), which indicate that long soaking is necessary to secure satisfactory ductility.

Typical mechanical properties of annealed material containing less than 0.35 per cent carbon, 0.25 to 0.80 per cent manganese, less than 1 per cent silicon, and 23 to 30 per cent chromium have been given as follows:(506)

Tensile strength, lb. per sq. in	80,000
Yield strength, lb. per sq in.	50,000
Elongation in 2 in., per cent	30
Reduction of area, per cent	50
Izod impact, ft-lb	2
Brinell hardness	163

Tensile properties of a steel containing somewhat higher carbon (0.53 per cent), 24.45 per cent chromium, and 0.39 per cent silicon, as determined by MacQuigg,(40) are plotted in Fig. 52. The steel was rolled from 5 × 5-in. ingots to ¼-in. plate from which flat specimens were cut. Edges of the specimens were milled, but the flat surface was unmachined. As is evident from Fig. 52, heating for 24 hr. at temperatures as low as 100 to 400°C. (210 to 750°F.) produces very different structural changes and thus different properties from a corresponding treatment for 1 hr. Tensile properties of two high-chromium steels containing 21 and 27 per cent chromium, determined by McAdam,(90,91) are given in Table 63, page 198.

Despite satisfactory tensile and yield strengths and, after certain thermal treatments, satisfactory elongation and reduction of area, all the data quoted in this section and the results obtained by McAdam(90,91) (Tables 62 and 63) indicate that the 20 to 35 per cent chromium steel has low resistance to single-blow impact, usually between 1 and 4 ft-lb. for a notched-bar Izod specimen. This may be compared with Izod impact values of 75 to 100 for annealed 18-8.

The work of Franks(360) and the recent investigation of Colbeck and Garner indicate that the notch toughness of low-carbon 20 to 35 per cent chromium steels can be greatly improved by the addition of nitrogen. Thus, for specimens of a steel containing 0.10 per cent carbon and 22.4 per cent chromium, water quenched

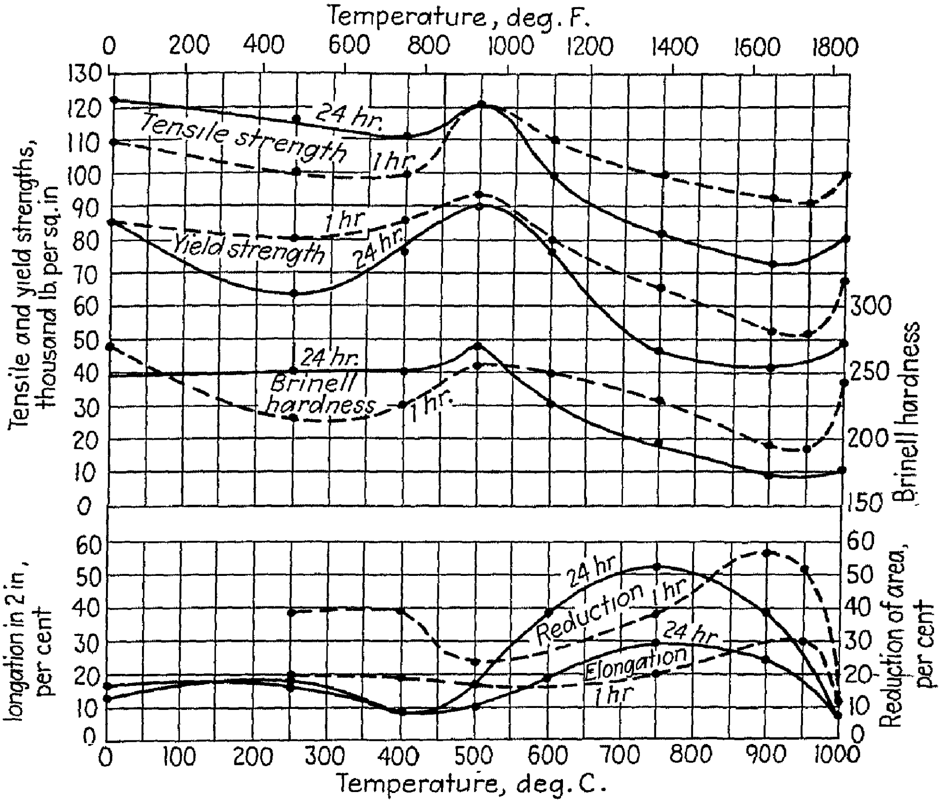

FIG. 52.—Effect of time at temperature on the mechanical properties of air-cooled steel containing 0.53 per cent carbon, 0.39 per cent silicon, and 24.45 per cent chromium. (*MacQuigg.*[40])

after holding 6 hr. at 900°C. (1650°F.), the properties as affected by nitrogen were found by Franks to be as follows:

Property	Nitrogen, per cent	
	0.032	0.21
Tensile strength, lb. per sq. in	77,600	85,000
Yield strength, lb. per sq. in..	46,500	54,000
Elongation in 2 in., per cent..	30	29
Reduction of area, per cent...	60	66
Izod impact, ft-lb............	4	24
Brinell hardness...	149	166

The recent investigation by Colbeck and Garner(518) shows that an excellent combination of properties results from water quenching the nitrogen-containing steels from a higher temperature, *viz.*, 1050 to 1200°C. (1920 to 2190°F.). In discussion of this paper Franks stated that his investigations* confirmed that a high quenching temperature improved the toughness of the steels. Some of the results of Colbeck and Garner and of Franks are collected in Table 59. The steels tested by Colbeck and Garner were made in small lots, and the tests were performed on ⅜-in. specimens. The work was extended to investigation of the effect of tempering on those water-quenched high-nitrogen steels which showed high impact as quenched. The toughness was found to be unaffected by tempering temperatures up to 400°C. (750°F.).

Above this temperature the impact value falls fairly rapidly with increasing temperature and after tempering at 800°C. (1470°F.) the specimens were quite brittle.

TABLE 59.—EFFECT OF NITROGEN ON THE MECHANICAL PROPERTIES OF HIGH-CHROMIUM STEELS, WATER QUENCHED FROM 1050 TO 1150°C. (1920 TO 2100°F.)

Investigator	Ingot No	Composition, per cent				Tensile strength, lb./sq. in.	Yield strength, lb /sq in.	Elongation, per cent	Reduction of area, per cent	Izod impact, ft-lb
		C	Cr	Ni	N_2					
Colbeck and Garner(518)*	*X*370	0.10	21.0		0.04	78,400	62,700	10	15	2.4
	*X*378	0.10	21.1	0.55	0.20	136,600	47,000	30	15	19.8
	*X*357	0.13	25.0		0.11	95,000	66,100	23	46	2.4
	*X*361	0.07	24.9		0.31	107,500	72,800	40	62	45.5
	*X*362	0.14	24.9	1.14	0.29	105,200	67,600	50	63	115.5
	*X*401	0.12	27.8		0.06	69,400	67,200	3	3	21.0
	*X*409	0.12	27.1	1.73	0.09	89,600	78,400	5	3	1.2
	*X*410	0.12	27.1	1.80	0.33	108,400	78,000	38	58	89.1
Franks†.		0.17	25.0	2.00	0.04	96,500	71,500	30	48	
		0.18	25.0	2.00	0.15	113,000	76,500	44	63	107
		0.14	22.0	1.00	0.04	92,500	65,000	25	39	6
		0.15	22.0	1.00	0.10	129,000	68,000	36	44	48
		0.12	22.0	1.00	0.15	110,000	60,000	42	49	82
		0.15	22.0	1.00	0.20	117,500	65,000	46	52	119

* The steels were water quenched after 2 hr. at temperature

† See footnote below. The steels were water quenched after 30 min. at temperature

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* *Electrometallurgical Company Bulletin*, privately printed, 1936.

TABLE 60.—TRANSVERSE AND TENSILE PROPERTIES OF SOME CAST HIGH-CHROMIUM STEELS

Investigator	Composition, per cent				Transverse properties				Tensile properties				
	C	Mn	Si	Cr	Size of specimen, in	Distance between supports, in.	Transverse strength, lb.	Deflection, in.	Tensile strength, lb./sq. in	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
MacQuigg(40)	0.27	...	...	27	¾ sq	12	3,350	0.53					
	1.16	...	..	27.17	1⅛ sq.	12	8,370	Nil					
	2.63	...	.	27.62	¾ sq.	4	12,510	Nil					
MacQuigg(380)	0.35	...	..	25.08	....	...	...		59,000	51,000	1.0	1.0	169
									58,000*	45,000*	2.0*	3.0*	149*
Houdremont and Wasmuht(182)	1.1	0.42	1.3	33.6	1.18 rd.	23.6	73,000†	0.20	55,500	......	Nil	...	250
	2.3	0.40	1.4	34.2	1.18 rd.	23.6	77,400†	0.23	61,500	.....	Nil	..	300
	3.1	0.38	1.2	34.9	1.18 rd	23.6	74,800†	0.23	66,000	...	Nil	..	350
Simonds(127)	<0.35	..	.	18	..	..	....		75,000	50,000	15	....	200
	<0.50	..	.	28	..	..	..		50,000	35,000	3	..	170

* As cast, then heated 2 hr. at 850°C. (1560°F.), furnace cooled to 600°C. (1110°F.), and water quenched.

† In lb per sq. in

109. Mechanical Properties of High-chromium Steel Castings. Mechanical properties of some cast alloys, determined by MacQuigg,(40,380) Houdremont and Wasmuht,(182) and Simonds,(127) are collected in Table 60. From the reported values it seems doubtful whether these alloys should be classed as cast steels or as cast irons. Houdremont and Wasmuht's alloys, with 1.2 to 1.4 per cent silicon, are high enough in this element to be classed as cast irons; the other alloys tested, with considerably less than 1 per cent silicon, are clearly cast steels. For convenience, the Houdremont and Wasmuht alloys have been included in this tabulation.

MacQuigg's data indicate that the high-carbon alloys are strong and brittle, *i.e.*, they have no deflection. However, the alloys tested by Houdremont and Wasmuht showed an appreciable deflection, which can probably be explained by the much longer span used. MacQuigg also found that transverse strength and deflection vary with the casting temperature; for the alloy containing 0.27 per cent carbon and 27 per cent chromium the results were as follows:

Casting temperature*	Breaking load, lb.	Deflection, in.
High	1650	0.20
Low	3350	0.50

* No actual temperatures given.

As is evident from Simonds'(127) data in Table 60, the tensile strength, yield strength, elongation, and hardness of a cast 28 per cent chromium steel are much lower than the corresponding properties of the cast 18 per cent chromium steel.

The effect of nitrogen on the tensile properties of cast 25 per cent chromium steels is shown by the data of Table 61, which may be compared with those given by MacQuigg for the 25 per cent chromium steels with normal low nitrogen content.

110. Endurance Limit of Wrought High-chromium Steels.—The endurance limits of a series of chromium steels, tested in air, in fresh water, and in salt water, were determined by McAdam.(90,91) The composition and heat treatment of some of these steels are given in Table 62 and their tensile and endurance properties in

TABLE 61.—MECHANICAL PROPERTIES OF HIGH-NITROGEN 25 PER CENT CHROMIUM STEEL CASTINGS*

Composition, per cent				Condition	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Transverse tests†		Brinell hardness
C	Cr	N	Ni					Breaking load, lb.	Deflection, in.	
0.32	24.21	0.20	0.15	As cast Heat treated‡	82,000 81,400	63,000 52,200	3 15	7800 ...	0.3 ...	202 179
0.35	24.43	0.26	1.20	As cast Heat treated‡	96,500 103,000	76,600 61,000	3 6	8700 ...	0.53 ..	223 200

* Franks (267)

† 1.25-in. diameter tapered bar, load in the middle, 12 in. between centers.

‡ Heated 2 hr. at 850°C. (1565°F.); furnace cooled to 600°C. (1110°F.), then air cooled.

Table 63. These data show that for high-chromium steels the endurance limits (for 10^7 cycles) are proportional to the tensile strengths, but that the corrosion-endurance values deviate slightly. According to McAdam, these data justify the conclusion that increase in chromium from 12 to 20 per cent or more is accompanied by an increased value for fresh-water corrosion endurance; he warned, however, that other factors may complicate this. The same increase in chromium is accompanied by an increase in the value for salt-water corrosion endurance from

TABLE 62.—COMPOSITION AND HEAT TREATMENT OF STEELS TESTED BY McADAM(90,91)

Mark	Composition, per cent						Treatment
	C	Mn	Si	Cr	Ni	Cu	
GS	0.38	0.26	0.20	14.50	0.23	0.07	Oil quenched after 1 hr. at 980°C. (1800°F.), tempered 2 hr. at 650°C. (1200°F.), cooled in air
HH	0.24	0.46	0.64	17.09	0.01	0.07	Annealed by the manufacturer
HI	1.20	0.41	1.13	17.74	0.12	0.09	Furnace cooled after 1 hr. at 925°C. (1700°F.)
GQ	0.19	0.31	0.55	20.94	0.17	0.92	Annealed by the manufacturer
HR	0.20	0.32	0.28	27.37	0.19	0.04	Annealed by the manufacturer

25,000 to 30,000 lb. per sq. in. Corrosion-endurance limits of the high-chromium steels apparently have little relation to ordinary mechanical properties; they are 50 to 100 per cent higher than the values for carbon or low-alloy steels tested under identical conditions.

TABLE 63.—MECHANICAL AND ENDURANCE PROPERTIES OF HIGH-CHROMIUM STEELS

Mark	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Charpy impact, ft-lb.	Fatigue limit (for 10^7 cycles), lb./sq. in., in		
							Air	Fresh water	Salt water
GS	117,400	56,000	41,200	21.0	52.3	13.4	54,000	38,000	26,000
HH	87,700	39,300	25,300	29.2	61.3	7.6	46,000	44,000	26,000
HI	107,000	46,700	36,000	16.3	30.0	1.3	59,000	37,000	25,000
GQ	87,900	47,800	40,000	27.9	52.2	2.4	47,000	42,000	30,000
HR	81,000	44,500	26,300	28.0	57.0	2.9	44,000	38,000	30,000

* McAdam.(90,91)

111. Short-time Elevated-temperature Properties.—The steels containing 20 to 35 per cent chromium are used chiefly for their scale resistance in many applications under stress for a long period of time. As a result, investigators have been more interested in the creep strength of these materials than in their short-time tensile properties. However, the data of Table 64, obtained by a producer(486) of these steels, are of interest. They show that a typical wrought steel containing a maximum of 0.25 per cent carbon, 1 per cent manganese, 0.50 per cent silicon, and between 23 and 30 per cent chromium undergoes an increase in strength on heating between 100 and 400°C. (210 and 750°F.), and when the temperature exceeds 500°C. (930°F.), the strength steadily decreases until it reaches a value of only 3700 lb. per sq. in. at 1230°C. (2250°F.). Thus, at slightly elevated temperature these high-chromium steels act similarly to ordinary carbon steels, which exhibit strengthening on heating in the range 300 to 400°C. (570 to 750°F.). In the report from which the tensile-strength data in Table 64 were taken, no elongation values were given. Values reported by MacQuigg(40) for a steel of approximately the same composition indicate that the elongation remains approximately constant as the testing temperature increases from normal to 600°C. (1110°F.); at higher temperatures it increases until, at 900°C. (1650°F.) or above, it exceeds 75 per cent in 2 in.

TABLE 64.—SHORT-TIME HIGH-TEMPERATURE TENSILE TESTS ON LOW-CARBON 23 TO 30 PER CENT CHROMIUM STEEL*

Temperature		Tensile strength, lb. per sq. in.
°C.	°F.	
Room	Room	75,000 to 100,000
100	210	116,000
400	750	109,000
500	930	95,000
600	1110	52,000
700	1290	34,000
800	1470	18,000
900	1650	8,500
1000	1830	6,200
1150	2100	5,000
1230	2250	3,700

* Allegheny Ludlum Steel Corporation.(486)

In an investigation of the resistance of various low- and high-alloy steels to hot deformation, Hennecke(70) used static and single-blow dynamic compressive tests on accurately machined cylindrical specimens. Under these test conditions, a steel containing 0.06 per cent carbon and 24 per cent chromium (other elements were low) showed a steady decrease in resistance to hot deformation with increasing temperature. This is in contrast to the behavior of the steels that undergo alpha-gamma transformation, which show a slight strengthening in the temperature range of the allotropic change. Above 800°C. (1470°F.) the values obtained for resistance to deformation were lower than for the low-alloy steels that were essentially pearlitic in structure. This leads to the conclusion that, although chromium increases the resistance of iron to hot deformation, its effect as compared with carbon is small.

Houdremont and Wasmuht(182) determined the effect of temperature on the tensile strength of their cast alloy *B*, which contained 2.3 per cent carbon, 1.4 per cent silicon, and 34.2 per cent chromium. Results were as follows:

Temperature of test		Tensile strength, lb. per sq in.
°C.	°F.	
20	70	58,500
500	930	65,500
600	1110	40,500
800	1470	15,000
900	1650	9,400
1000	1830	6,400

112. Creep Strength.—The creep data from various sources on low-carbon 25 per cent chromium steels are not consistent, but they show, for instance, that increasing the chromium content from 12 to 25 per cent produces a large decrease in creep strength at temperatures between 540 and 730°C. (1000 to 1350°F.). This is illustrated by the data summarized in Table 65. Included for comparison are the stress values for unalloyed steels containing 0.08 to 0.17 per cent carbon. It is evident that in long-time tests the low-carbon 25 to 30 per cent chromium steels are not so strong as plain low-carbon steel at temperatures of 540 to 650°C. (1000 to 1200°F.).

TABLE 65.—STRESS FOR 1 PER CENT CREEP IN 10,000 HR. OF LOW-CARBON CHROMIUM STEELS*

Approximate composition, per cent			Stress, lb per sq. in., at			
C	Cr	Ni	540°C. (1000°F.)	650°C. (1200°F)	730°C (1350°F.)	815°C. (1500°F.)
0.05 to 0.15	17 to 19	8 to 10	17,000	7000	3000	850
0.10 max.	12 to 14	. . .	13,000	2300	1400	
0.10 max.	16 to 18	. . . .	8,500	2100	1200	
0.10 max.	25 to 30	. . . . .	1,600	400		
0 08 to 0.17†	. . . . . .	. .	4,000	800		

* United States Steel Corporation.(301)

† From "The Alloys of Iron and Carbon," Vol. II,(472) p. 515

On the other hand, the data of Table 65 are not confirmed by those of Fig. 53, which gives the creep stress for a commercial wrought 25 per cent chromium steel(486) containing a maximum of 0.25 per cent carbon. These data show that the 25 per cent chromium steel is appreciably stronger at 650°C. (1200°F.), for example, than the ordinary carbon steel.

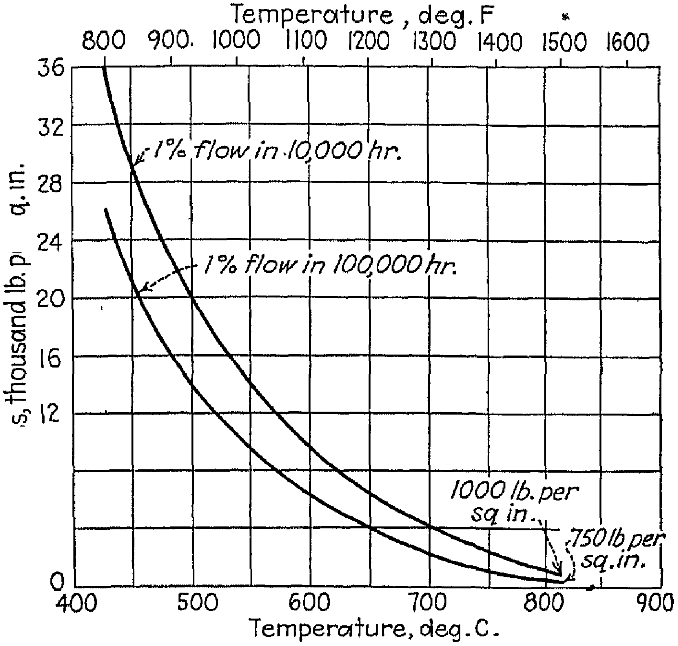

FIG. 53.—Creep stress for an elongation of 1 per cent in 1000 and 10,000 hr. for a steel containing 0.25 per cent carbon and 25 per cent chromium (*Allegheny Ludlum Steel Corporation.*(486))

TABLE 66.—STRESS FOR A CREEP RATE OF 0.0001 PER CENT PER HR., AFTER A PERMANENT ELONGATION OF 0.2 PER CENT*

Approximate composition, per cent		Stress, lb. per sq. in., at					
Cr	Ni	600°C. (1110°F.)	650°C. (1200°F.)	700°C. (1290°F.)	750°C (1380°F.)	800°C. (1470°F.)	900°C. (1650°F.)
16	35	9,600	7800	6100	4500	3300	1300
25	20	10,000	7400	5400	3400	2600	1000
25	. .	8,400	5000	2800	1700	1100	400
28		5,100	3600	2600	1600	1000	300

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* Müller-Berghaus.(328)

Reduced creep strength at temperatures of 600°C. (1110°F.) or above, with increasing chromium, is indicated by the values of Müller-Berghaus(328) in Table 66. The carbon content of these alloys is not given, and the method of determining creep and reporting the results was not the same as for the values collected in Table 65.

TABLE 67.—STRESSES PRODUCING COMPARABLE LIFE BEFORE FAILURE FOR THE FOLLOWING TWO STEELS*

Element	Percentage	
	Cr-Cu steel	High-speed steel
Carbon....	0 28	0.77
Manganese.	0.38	0.24
Silicon ...	0.17	0.42
Chromium	20.5	3.9
Tungsten..	....	13.1
Vanadium	.....	1.9
Copper	0.98	

Steel	Stress before failure, lb. per sq. in., for a life of				
	10 hr.	100 hr.	500 hr.	1000 hr.	2000 hr
	Tested at 595°C. (1100°F.)				
Cr-Cu. ..	15,000	9,500	7,500	7,000	6,500
High-speed.	19,000	12,000	10,500	10,000	9,500
	Tested at 730°C (1350°F.)				
Cr-Cu.	5,500	2,500	1,500	1,000	800
High-speed.	8,000	5,000	3,000	2,000	1,500

* French.(68)

In an investigation of creep testing, French(68) used a high-speed steel and a high-chromium steel containing copper. The chromium-copper steel was water quenched from 1000°C. (1830°F.) and tempered at 650°C. (1200°F.). The high-speed steel was tested "as received." Of the various testing methods used by French, the one most suitable for a comparison of the two steels was the determination of the stress that resulted in a specific life (expressed in hours) before failure. The data are given in Table 67. Under these test conditions, the high-chromium steel did not withstand so high a stress for a given life at elevated temperatures as did the high-speed steel.

Stresses, for various creep rates, for 13, 17.6, and 27 per cent chromium steels (containing respectively 0.11, 0.10, and 0.20 per cent carbon), determined at 650°C. (1200°F.), were reported by White and Clark(409) as follows:

Creep rate in 1000 hr., per cent	Stress, lb. per sq. in.	
	13 and 18 per cent chromium steels	27 per cent chromium steel
1	2800	2700
0.5	2600	2100
0.1	2100	1300
0.05	1950	1200
0 01	1400	1000

Creep stresses for the various rates were the same for the 13 and 18 per cent chromium steels; the values for the 27 per cent chromium steel were uniformly lower.

To summarize, it may be said that the creep data for 20 to 30 per cent chromium steels are so conflicting that only the following conclusions are justified: (1) the creep stress for an elongation of 0.1 per cent in 1000 hr. is not much above the creep stress for unalloyed carbon steels at temperatures of 600°C. (1110°F.) and somewhat above; (2) in general, the creep strength decreases as the chromium increases from 15 to 30 per cent; and (3) more precise data are urgently needed.

D. CORROSION AND OXIDATION RESISTANCE

In general, iron-chromium alloys, especially those containing 20 to 35 per cent chromium, are highly resistant to all corroding conditions that are strongly oxidizing; this is true for both liquid and gaseous media, at room or elevated temperatures. These materials probably owe their corrosion resistance to the nature of the oxide coating formed, which affords more or less complete protection for the underlying metal. This oxide coating may be an invisible layer a few molecules thick,(187) or it may be a tough, adherent, refractory scale that visibly forms at high temperatures. Corroding media that do not cause this oxide layer to form are usually destructive and corrode the 20 to 35 per cent chromium steels rapidly. For example, under certain conditions, these materials may be almost completely passive when attacked by nitric acid, but under the same conditions, they may be rapidly destroyed by hydrochloric acid.

Before reviewing the data on the corrosion of the 20 to 35 per cent chromium steels, it should be emphasized again that in most cases they are valid only for the specific conditions under which they were obtained; generalizations should not be drawn too hastily. The chief value of reviewing such data is that important comparisons emerge.

113. Principal Factors Affecting the Corrosion of 20 to 35 Per Cent Chromium Steels.—Generally, to obtain optimum corrosion resistance, the carbon content of the 20 to 30 per cent chromium steels should be low, preferably less than one one-hundredth of the chromium content, and should be in solution. In some cases this may not be true, because Strauss and Talley(57) have shown that free carbide is not always responsible for loss of corrosion resistance. They found no more corrosion by salt spray in a 20 per cent chromium steel containing 0.24 per cent carbon and 1.08 per cent copper when slowly cooled from 980 to 1205°C. (1800 to 2200°F.) than when quenched from this temperature range. On the other hand, a steel containing 0.64 per cent carbon and 27 per cent chromium was attacked considerably by the same medium, if annealed; but the amount of corrosion could be lessened by quenching from 1095°C. (2000°F.).

It is almost unnecessary to remark that surface conditions have a great effect on the resistance of a material to corrosion. Even if a corroding medium normally forms a continuous protective film on the surface of a metal, any imperfection (*e.g.*, seams, large inclusions, or entrapped slag) is likely to produce an irregularity or even a break in this film, which thus results in a spot where failure may start. The effect of surface irregularities in setting up galvanic or concentration cells is so well known that detailed discussion is unnecessary.

A factor that is not generally recognized is the effect of strains at the surface. Kalling and Pagels(71) found that when a steel containing 0.07 per cent carbon, 1.06 per cent silicon, 0.16 per cent manganese, and 23.6 per cent chromium was cold worked, the corrosion in various reagents increased. The original high resistance of this steel could be restored by holding it until thoroughly soaked at a temperature of 175°C. (345°F.), which is below the temperature at which temper colors form. These investigators also found that surface strains are gradually eliminated at room temperature, but the time required is relatively long. They warned that too strenuous polishing may produce surface strains and thus may actually reduce instead of increase corrosion resistance.

114. Resistance to Nitric Acid.—The resistance to nitric acid of steels containing 10 to 35 per cent chromium is high (see Chapter IV, page 99); in general, the steels of the higher chromium ranges are more resistant, especially to acids of low concentration, than the lower chromium materials. For example, Thompson(78) found that in nitric acid containing 25 to 68 per cent HNO_3 by weight (at room temperature), steels containing 10 to 29 per cent chromium and 0.06 to 0.70 per cent carbon were equally resistant; the weight loss was less than 0.1 mg. per sq. dm. per day; but in acid concentrations of 1.5 to 15 per cent by weight, the steels containing 20 to 30 per cent chromium were attacked less than the ones containing 10 to 15 per cent chromium.

Endo(97) could find no measurable corrosion on annealed 23 and 29 per cent chromium steels (0.30 per cent carbon) after 5-hr. immersion in 400 cu. cm. of 5 per cent nitric acid at room temperature. Under the same conditions and with the same carbon content and treatment, a steel containing 19.17 per cent chromium lost 0.00007 g. per cu. cm., but a steel containing 12.40 per cent chromium lost 0.02402 g., and one containing 10.07 per cent chromium lost 0.04045 g. Endo used polished cylinders 4 mm. (0.156 in.) in diameter and 25 mm. (0.984 in.) long.

The resistance of wrought 0.16 per cent carbon, 25.65 per cent chromium steel (0.44 per cent silicon and 0.58 per cent manganese) is shown by the (unpublished) data in Table 68. Samples that had been water quenched after 6 hr. at 900°C. (1650°F.) were immersed in boiling 65 per cent nitric acid for 5 periods of

48 hr. each. At the end of each period the acid was renewed, and the loss calculated to inches penetration per month.

TABLE 68.—CORROSION OF LOW-CARBON 25 PER CENT CHROMIUM STEEL IN BOILING 65 PER CENT NITRIC ACID

Period	Penetration, in. per month	Weight loss, mg. per sq. dm. per day
First 48 hr.	0.00064	41.6
Second 48 hr	0.00056	36.4
Third 48 hr..	0.00064	41.6
Fourth 48 hr	0.00065	42.3
Fifth 48 hr	0.00061	40.0

The corrosion resistance of the 20 to 35 per cent chromium steels in nitric acid may be seriously impaired by the presence of chloride. Monnartz(7) found this to be the case for very low carbon alloys containing 20 to 40 per cent chromium when 5 per cent sodium chloride was added to dilute nitric acid.

The fundamentally high resistance of the 20 to 35 per cent chromium steels in nitric acid is confirmed by the data of several investigators, including MacQuigg,(49) Rohn,(76) and Guertler and Ackermann.(99) Mention should be made of Rohn's finding on the effect of carbon and melting practice. A steel containing 0.25 per cent carbon and 25 per cent chromium showed after 1 hr. a much greater solubility (0.01 to 0.2 g. per sq. dm. against no measurable loss) in hot 10 per cent nitric acid than a similar alloy essentially carbon-free and vacuum-melted from materials of the highest attainable purity.

115. Resistance to Hydrochloric and Sulphuric Acids.—Hydrochloric and sulphuric acids usually corrode the 20 to 35 per cent chromium steels rapidly; unless conditions are such that passivity can be induced, these steels should not be used in contact with either of the acids. Although the boundary between activity and passivity is a definite one, it is affected by a number of factors, especially the oxidizing capacity of the acid, its hydrogen-ion concentration, and the chemical composition and thermal treatment of the steel. The whole question of the passivity-activity relation and corrosion of alloy steels in mineral acids has been adequately discussed by McKay and Worthington(431) and needs no further attention here. In general, it may be said that unmodified 20 to 35 per cent chromium steels are never passive to hydrochloric acid and are passive to sulphuric acid only under very definite and restricted conditions.

For corrosion resistance to hydrochloric acid, the chromium and carbon contents of a steel are of minor importance(76); apparently the only method of increasing resistance is to add relatively large amounts of molybdenum, tungsten,(156) or copper, or a combination of all these; but even if these metals are added, there is no certainty that the resulting steel will be passive except under very restricted conditions.

Sulphuric acid is highly corrosive to the 20 to 35 per cent chromium steels under certain conditions; under other conditions passivity may be induced. This has been studied by Monnartz,(7) Aitchison,(8) MacQuigg,(49) Rohn,(76) Guertler and Ackermann,(99) Pilling and Ackerman,(123) and others, some of whom(7,99) have reported that corrosion increases with the chromium content. Guertler and Ackermann's results indicated uniform corrosion in sulphuric acid of specific gravity 1.005 with chromium contents of 15 to 22 per cent and marked increase with higher percentages.

Of interest in regard to establishing passivity of high-chromium steels is the observation by Pakulla and Oberhoffer(62) that polished metallographic specimens of steels containing more than 30 per cent chromium are passive in 10 per cent sulphuric acid for several hours and are then attacked with great intensity.

116. Resistance to Other Acids.—According to Pilling and Ackerman,(123) chromium steels containing 20 to 35 per cent chromium are passive in pure 5 per cent sulphurous acid. The borderline between activity and passivity lies between 15 and 20 per cent chromium as shown by the following data:

Chromium, per cent	Loss in 54 min., mg. per sq. dm.
10	4000
13	5500
15	4000
17	3
20	4
23	1
29	1
33	1

The presence of sulphuric acid or sodium chloride in the sulphurous acid may destroy the passivity.

Published data on the corrosion of these high-chromium steels in phosphoric, chromic, and acetic and other organic acids have been summarized by McKay and Worthington.(431) The results of tests with phosphoric acid are erratic; in some it has been shown that the steels are passive, in others rapid corrosion rates have been indicated. McKay and Worthington stated that

> obviously the resistance of chromium alloys to phosphoric acid is extremely sensitive to some unknown factors. . . . Based on indirect evidence it may be said that the presence of ferric iron (in the phosphoric acid) tends strongly to make the alloys passive, and the presence of chlorides and other halides and of reducing agents—possibly phosphorus in intermediate degree of oxidation—to make them active.

High-chromium steels are normally passive in chromic acid; if, however, the chromic acid is used together with a strong, hot, non-oxidizing acid, corrosion by the latter is accelerated. In acetic and other organic acids, such as formic, tartaric, citric, lactic, malic, or oxalic, iron-chromium alloys are passive provided that considerable nickel is present and the acid is at room temperature. According to McKay and Worthington, iron-chromium alloys containing no nickel, although showing a strong tendency to be passive, usually corrode at rates ranging from 25 to 2500 mg. per sq. dm. per day.

Johnson(46) reported that a 27 per cent chromium steel was passive in 85 per cent formic acid at room temperature but corroded readily at 95°C. (200°F.). It was also corroded by 25 per cent lactic acid at 95°C. but was passive in 25 per cent gallic acid at the same temperature.

Enough has been cited to show that one of the outstanding characteristics of the 20 to 35 per cent chromium steels is their tendency to be passive and thus corrosion resistant in oxidizing acids. A statement by McKay and Worthington(431) sums up the case concisely:

> The range of solutions in which passivity takes place is a very broad one. Yet, with many solutions there is a point as the conditions become more severe, where a slight change in some condition—increase in temperature, decrease in oxidizer, or change in concentration—throws the metal from a state of passivity to one of activity. In general the

chromium alloys in the active condition are rapidly corroded, in the passive condition virtually unattacked or relatively slowly attacked. The passivity-activity boundary, shifting often with delicate changes in exposure condition and likewise with delicate changes in the composition and structure of the alloy, becomes in a sense the limit of usefulness of the alloy.

117. Resistance to Air, Water, Salt, and Other Media.—The resistance to the atmosphere of chromium steels containing more than 10 per cent chromium is discussed in detail in other chapters of this monograph. It suffices here to add only a few words concerning the resistance of the 20 to 35 per cent chromium steels. In general, the low-carbon steels are unaffected even after long exposure to average rural and urban atmospheres. However, if the carbon content is high, *e.g.*, 2 per cent, the steels rust, but not progressively, during long exposures to the atmosphere. Both high- and low-carbon steels resist sulphurous industrial atmospheres better than the steels containing less than 20 per cent chromium. This betterment is strictly relative; in a moderately sulphurous atmosphere they remain unaffected, while a 14 per cent chromium alloy is discolored; in a strongly sulphurous atmosphere they may discolor and even pit, but they are definitely superior to the lower chromium steels. Except for precious metals, the low-carbon high-chromium steels, either with or without nickel, are more resistant to various atmospheric conditions than any other metal.

The general resistance of the chromium steels to distilled water, as affected by carbon content, is shown by Fig. 54 from a paper by Roesch.(436) He divided the steels into the following classes: (1) steels that are non-rusting without heat treatment; (2) intermediate alloys that are non-rusting after heat treatment; and (3) rusting alloys. For a given chromium content, (1), (2), and (3) occur in the direction of increasing carbon content, and, in the 10 to 40 per cent chromium range shown, the required chromium for non-rusting increases with carbon content.

The resistance of high-chromium steels to salt solutions depends primarily on whether the solution contains sufficient dissolved oxygen to maintain an impervious oxide film on the surface of the metal. Aitchison(8) investigated the resistance to 3 per cent sodium chloride solution of a series of chromium steels containing about 0.85 per cent carbon, which had been air cooled from 900°C. (1650°F.). The steels containing 20 to 24 per cent chromium were much more resistant than the ones containing 10 to 15 per cent chromium; the average loss in weight of the former in 77 days ranged from nothing up to 0.0024 g. per sq. cm., whereas the average loss of the lower chromium material was between 0.0079 and 0.0131 g. per sq. cm.

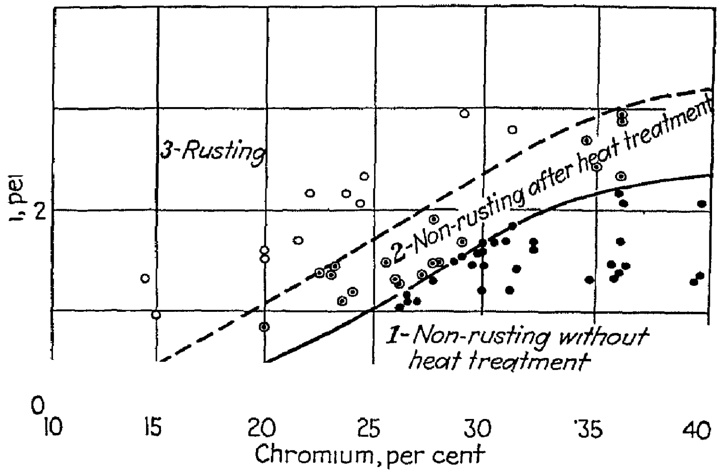

FIG. 54.—Effect of composition on the corrosion of high-chromium steels in distilled water (*Roesch.*(436))

Colbeck and Garner(518) determined the relative attack of two 25 per cent chromium steels, one of which contained nitrogen and 1 per cent nickel, as compared with 18-8, in boiling 25 per cent ammonium chloride solution. The specimens were forged bars ½ in. and ⅞ in. in diameter, water quenched after holding 2 hr. at 1100 to 1125°C. (2010 to 2055°F.), and were immersed for 1040 hr. in the solution. Results are given in Table 69.

TABLE 69.—RELATIVE CORROSION OF 25 PER CENT CHROMIUM STEELS AND 18-8 BY BOILING AMMONIUM CHLORIDE*

Composition, per cent				Surface area, sq. cm.	Weight loss, g. per sq. m. per 24 hr.
C	Cr	Ni	N_2		
0.12	19.0	8.13		16,523	0.2947
0.13	25.0	Nil	0.11	8,465	0.8287
0.11	25.2	1.12	0.24	12,411	0.5320

* Colbeck and Garner.(518)

These preliminary results indicate that the addition of nitrogen improves the corrosion resistance of low-carbon 25 per cent chromium steel under the experimental conditions used.

Strauss[(407)] tabulated the relative corrosion resistance of a number of alloy steels in various media. He rated two high-chromium steels as follows:

Corroding medium	17 per cent chromium, 0.10 per cent or less carbon	27 per cent chromium, 0.50 per cent or less carbon
Sea water	Good	Good
Aqueous ammonium chloride ..	Good	Excellent
Aqueous magnesium chloride ..	Good	Excellent
Aqueous magnesium sulphate....	Good	Excellent

In this tabulation, the term "good" covers those materials that have corrosion rates low enough so that they can be used in permanent construction; "excellent" signifies that the steel will give almost unlimited service. Such rating is indefinite at best and should be used only to choose materials to be subjected to further tests simulating actual conditions as closely as possible.

High-chromium steels have been used extensively in coal mining for handling acid mine waters. These are usually very dilute sulphuric acid waters and contain sufficient ferric sulphate to maintain oxidizing conditions and thus produce passivity on the surface of the steel.

The value of salt spray as a test for corrosion resistance has been questioned frequently, but nevertheless it is still used to some extent as an acceptance test for corrosion-resistant materials. The test has been studied in detail by a number of workers; the results reported by Arness and Ostrofsky[(213)] are comprehensive and give a good picture of what may be expected from high-chromium steels in this test. To summarize, it was found that, either polished or unpolished, steels containing 0.06 to 0.21 per cent carbon and 12.5 to 26.5 per cent chromium had excellent resistance to salt-spray corrosion. The test is not sensitive to differences in heat treatment or slight differences in composition; resistance was found to improve as the chromium increased from 13 to 17 per cent, with little or no further improvement for higher chromium percentages. Polishing the surface increased resistance, and removing the products of corrosion resulted in marked improvement upon further exposure. Most important was the conclusion that the salt-spray test is not a direct measure of corrosion resistance and that "no direct parallel can be drawn between resistance in the salt-spray test and rust resistance under service conditions."

High-chromium steels are ordinarily completely resistant to ammonia solutions; their corrosion rates are usually less than 1 mg. per sq. dm. per day. They are passive to food products, with very low corrosion rates in fruit juices, milk, and such substances. Because these materials are not so readily welded as the 18-8 and other austenitic alloys, the latter are more commonly employed. At room temperature, the 20 to 35 per cent chromium steels are very resistant to caustic alkalis; at elevated temperatures, however, they may not be so resistant as commercially pure iron.

The literature on the corrosion of chromium steels in the atmosphere and in acids, alkalis, salt solutions, water, and food products has been so adequately summarized by McKay and Worthington(431) that further review is unnecessary in this chapter except for a brief discussion of cast alloys. As a general summary it may be stated that the 25 to 30 per cent chromium steels have better all-round corrosion resistance than the materials containing 10 to 18 per cent chromium. They "have a wide utility, yet certain limitations appear in the processes of production and working and also in mechanical properties."(431) These limitations have restricted their use to applications in which their superior passivity more than compensates for the difficulty of welding them.

118. Corrosion Resistance of Cast High-chromium Steels.—Cast alloys containing 25 to 35 per cent chromium and 0.2 to 3 per cent carbon are widely used for resistance to oxidation at elevated temperature and to certain types of corrosion at room temperature. According to Furman,(269) most of them contain about 0.2 to 0.5 per cent carbon, which is high enough to ensure good casting properties, fine grain, and satisfactory mechanical properties, but which is not high enough to affect corrosion resistance deleteriously. Castings of this composition range (with about 29 per cent chromium) are almost completely resistant to acid mine waters,(35) and since 1922 their use as pump parts in handling these waters has increased steadily.

Furman noted that alloys containing about 0.5 per cent carbon and 28 per cent chromium are usually satisfactorily resistant to boiling 50 per cent nitric acid and to a boiling mixture containing 33.4 per cent nitric acid, 42.4 per cent sulphuric acid, and 24.2 per cent water. In a 24-hr. test such alloys showed corrosion equivalent to a penetration of 0.010 to 0.019 in. per year in the boiling nitric acid, and to a penetration of 0.35 to 0.37 in. per year in the boiling mixed acid. Furman's data indicate that carbon increases the corrosion rate in the boiling mixed acid. His results for steels containing 31.67 to 34.4 per cent chromium, about 0.85 per cent manganese, and 0.55 per cent silicon are reproduced in Table 70. For maximum corrosion resistance under conditions similar to those outlined, he recommended that the casting have a carbon content of about one one-hundredth of the chromium content.

Table 70.—Weight Loss of Cast High-chromium Steels in Boiling Acid Containing 33.4 Per Cent Nitric Acid, 42.4 Per Cent Sulphuric Acid, and 24.2 Per Cent Water*

Period	Weight loss, g. per sq. cm. per hr., × 100, for a carbon content of				
	0.124%	1.04%	1.49%	2.21%	3.10%
First hour	0.045	0.052	0.091	0.49	0.735
Second hour	0.043	0.0625	0.136	0.38	0.56
Third hour	0.0423	0.0545	0.142	0.475	0.60

* Furman.(269)

Houdremont and Wasmuht(182) recommended a composition of 34 per cent chromium with 1 to about 2.3 per cent carbon and about 1.2 to 1.4 per cent silicon for corrosion and heat resistance under a variety of conditions. According to Furman, the data given by these investigators "cannot be substantiated by results obtained from a similar alloy under actual service conditions in this country." The corrosion resistance of Houdremont and Wasmuht's alloys is discussed in the next chapter.

119. Scale Resistance to Gases Containing No Sulphur.—With the exception of some of the iron-nickel-chromium oxida-

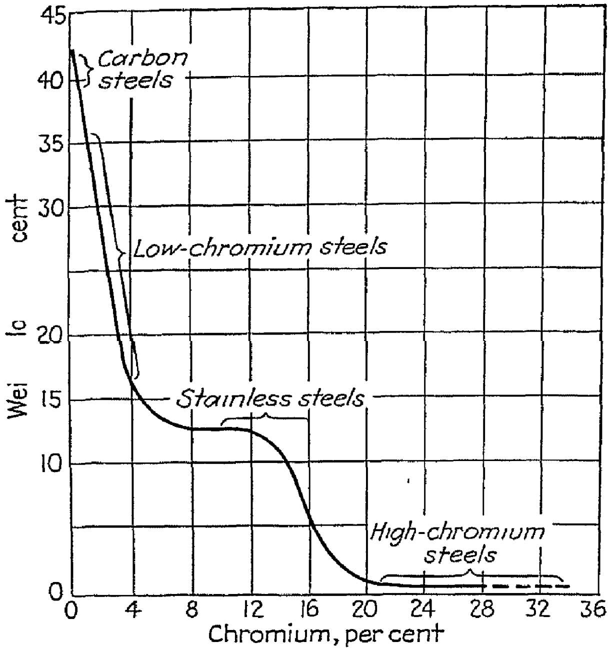

FIG. 55.—Effect of chromium on the weight loss of 0.5-in. steel cubes, heated 48 hr. at 1000°C. (1830°F.). (*MacQuigg.*(380))

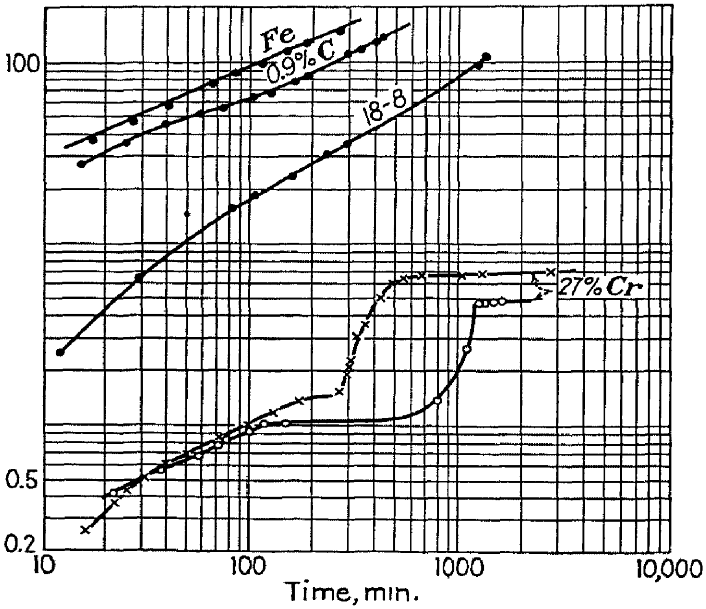

FIG. 56.—Relation between weight loss and time of exposure in air at 1100°C. (2010°F.) for low-carbon iron, carbon steel, and chromium steel. (*Heindlhofer and Larsen.*(275))

tion-resistant alloys, and some recently developed iron-chromium-aluminum alloys, the steels containing 20 to 35 per cent chromium are the most resistant of the ferrous alloys to oxidation at high temperatures. They are also much more resistant than the steels containing about 14 per cent chromium. This is shown clearly by Fig. 55, which gives the loss in weight on heating 0.5-in. cubes with ground surfaces for 48 hr. at 1000°C. (1830°F.). It is apparent that for maximum resistance to this temperature the chromium should be higher than 20 per cent.

According to Fry,(268) 18 per cent chromium is sufficient to reduce the scaling at 1000°C. (1830°F.) of a 0.5 per cent carbon steel to an inconsequential amount; if the scaling temperature is increased to 1100°C. (2010°F.), the chromium should be increased to about 30 per cent. Fry heated specimens for 240 hr. and determined the weight loss. Results were as follows:

Chromium, per cent	Loss, g. per sq. m. per hr., at	
	1000°C. (1830°F.)	1100°C. (2010°F.)
18	1	4
24	1	2
29	1	1

Heindlhofer and Larsen(275) tested in air at 1100°C. (2010°F.) specimens of low-carbon iron, 0.9 per cent carbon steel, 18-8, and a low-carbon steel containing 27 per cent chromium. The results are shown in Fig. 56. The time of heating was 40 hr. and the weight change was determined in a single heating period, so that the specimens were not subjected to intermittent cooling.

Noteworthy is the difference in the shape of the curves for the iron, the high-carbon steel, and the 18-8, which scaled uniformly, compared with the curve for the 27 per cent chromium steel, which scaled uniformly for the first 5 to 10 hr. only. Apparently the scale then broke and allowed fresh metal to be exposed to the air. After this, scaling was rapid; but the break soon healed and the rate of scaling slowed to almost zero.

Apparently carbon has much less effect on the elevated-temperature oxidation resistance of the 20 to 35 per cent chromium steels than it has on the corrosion resistance at room or slightly elevated temperatures. Furman(269) maintained that a 27 to 30 per cent chromium steel casting resists oxidation very satisfactorily up to 1040°C. (1900°F.) and satisfactorily "for most purposes" up to about 1150°C. (2100°F.), even if the carbon is as high as 3 per cent.

One of the most complete investigations of the oxidation resistance of iron-chromium alloys is that of Rickett and Wood,(335) who determined the effect of chromium content, time, temperature, and other variables. Specimens 0.5 in. in diameter and 1.5 in. long were exposed to dry commercial oxygen under carefully controlled conditions. The effect of composition may be summarized in a few words: At 980°C. (1800°F.), for exposures of 10, 50, and 150 hr., the gain in weight drops to less than 5 mg. per sq. cm. for chromium contents of more than 22 per cent.

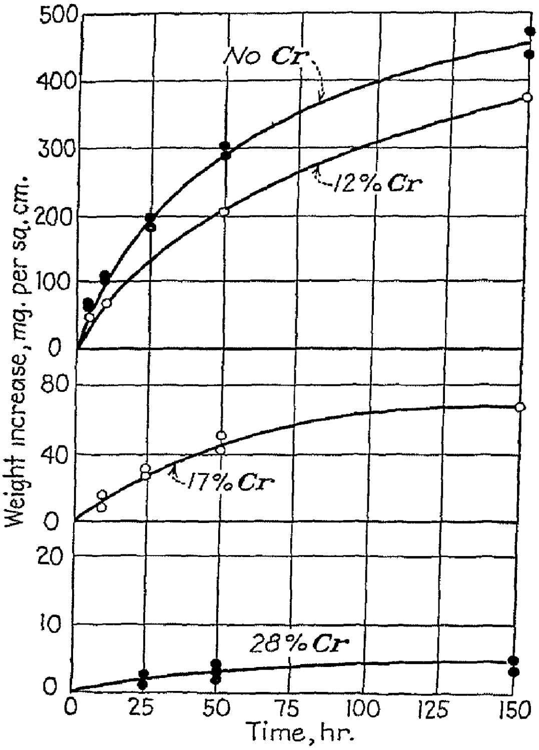

FIG. 57.—Effect of time and chromium content on the amount of oxidation of chromium steels at 980°C. (1800°F.) (*Rickett and Wood* (335))

The steels contained 0.12 to 0.20 per cent carbon, less than 0.5 per cent silicon, and between 0.4 and 0.8 per cent manganese;

chromium ranged from 11 to 28.5 per cent. One chromium-free steel containing 0.22 per cent carbon and 1.48 per cent manganese was included for comparison. Sulphur, phosphorus, and nickel were low in all the steels tested. The effect of time on oxidation at 980°C. (1800°F.) is shown in Fig. 57, and the effect of temperature in 25 hr. is shown in Fig. 58. The higher resistance of the 28 per cent chromium steels as compared with that of lower chromium material is clearly evident. Rickett and Wood also found that in tests at 980°C. (1800°F.) for 25 hr., tripling the amount of gas passed over the specimens per minute had no appreciable effect on the amount of oxidation.

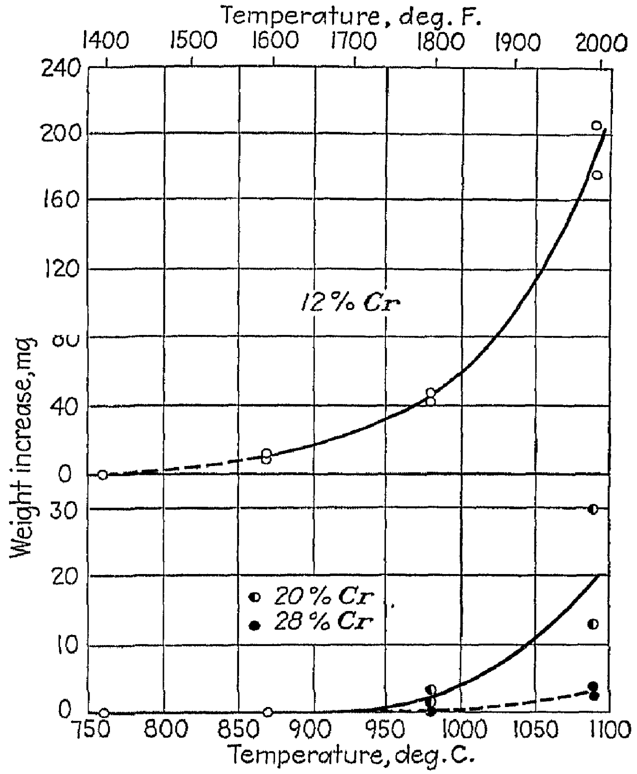

FIG. 58.- -Effect of temperature and chromium content on the amount of oxidation of chromium steels in 25 hr. (*Rickett and Wood.*(335))

The effect of time (up to 75 hr.) on the scaling of iron and chromium steels when tested in air at 900 and 1100°C. (1650 and 2010°F.) is shown in Fig. 59. These curves were given by Heindlhofer and Larsen(365) as representative for the materials used. The use of a logarithmic scale brings out clearly the increased resistance of the steels with increasing chromium content.

In an investigation of the composition of scale and its relation to the iron-oxygen system, Pfeil(122) found that in iron-chromium alloys the inner scale contained 3.5 times as much chromium as the original steel, while the two outer layers contained only a fraction of the chromium in the original steel.

120. Scale Resistance to Gases Containing Sulphur.—Sulphur in hot oxidizing gases is corrosive to high-nickel, nickel-chromium, and iron-nickel-chromium alloys, and sulphur in reducing gases is even more damaging, as the sulphide coating that forms is less protective than an oxide coating.(431) Available data indicate that, in general, for high-temperature use, when sulphur is present in the gases, 20 to 35 per cent chromium steels are more resistant than 10 to 18 per cent chromium steels and that they are more satisfactory in service than most of the iron-chromium-nickel alloys or even the nickel-chromium alloys.

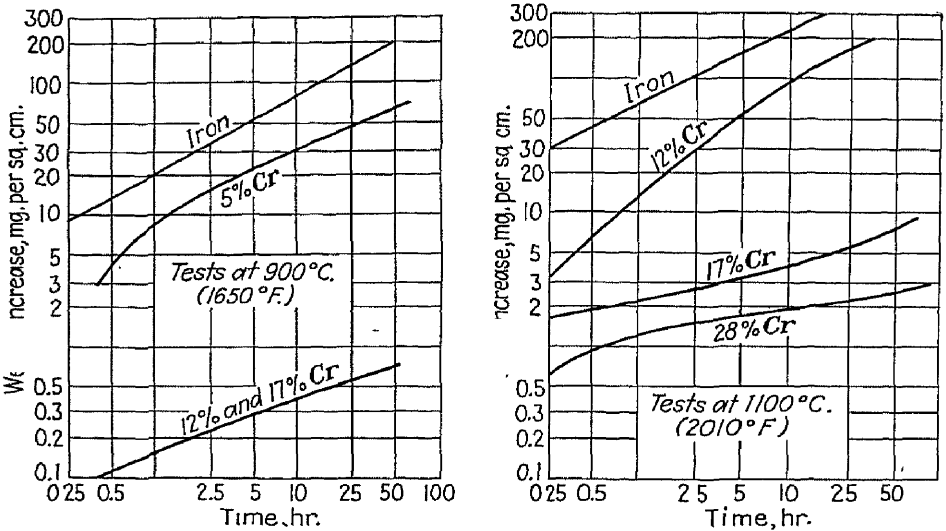

FIG. 59.—Effect of time and chromium content on the scaling of chromium steels at 900 and 1100°C. (1650 and 2010°F.). (*Heindlhofer and Larsen.*(365))

There are few specific data that would justify conclusions regarding the resistance of the 20 to 35 per cent chromium steels to sulphur-containing atmospheres. The few data available were nearly all obtained under reducing conditions, primarily in atmospheres of hydrogen sulphide. Scholl, according to French,(69) heated various materials for 28.5 hr. at 900°C. (1650°F.) in hydrogen sulphide with the following results:

Composition, per cent		Gain in weight, mg per sq. dm. per day
C	Cr	
0.16	..	2900
0.62	8	2500
0.10	14	1650
0.07	19	530
0.07	25	530

Greenwood and Roennfeldt(114) used a number of commercial scale-resisting alloys in a zinc-roasting furnace where they were exposed to gases containing about 5 per cent sulphur dioxide with the possibility that condensed lead sulphide was present. Their results were:

Composition, per cent			Rate of penetration, in. per year, after	
C	Cr	Ni	24 hr. at 1050°C. (1920°F.)	96 hr. at 900°C. (1650°F.)
1.5 to 3	25 to 30	..	4.7 to 8.8	1.1 to 1.5
1.0	22	25	11	4.3
0.9	17	34	14	3.3
0.67	19	40	8.8	4.0

Specimens (60 × 30 × 12 mm.) of various materials, ground to remove scale, were heated by Gruber(141) in hydrogen to various testing temperatures. The hydrogen was then replaced for 1 hr. by hydrogen sulphide, after which hydrogen was again passed over the specimens while they cooled to room temperature. The relative gain in weight is shown in Table 71. Noteworthy is the resistance of the 25 per cent chromium steel to which 10 per cent aluminum had been added. In these tests there was little difference between the 25 per cent chromium alloy and the alloy containing 25 per cent chromium and 25 per cent nickel.

Rickett and Wood(335) tested steels with various chromium contents and at various temperatures (see page 216 for details of methods) in a mixture of hydrogen sulphide and nitrogen containing 20 per cent H_2S by volume. After 50 hr. at 980°C. (1800°F.), the gain in weight of the specimens was as follows:

Chromium, per cent	Gain in weight, mg. per sq. cm.
0	1000
11	975
20	940
28	840

The superiority of the higher chromium steel after heating 25 hr. is somewhat more pronounced at a higher temperature, *viz.*,

Temperature of test		Gain in weight, mg. per sq. cm	
°C.	°F.	11% Cr	28% Cr
980	1800	620	550
1095	2000	1000	790

Table 71.—Relative Resistance of Iron, Chromium, and Iron-chromium Alloys to Hydrogen Sulphide*

Composition, per cent				Weight gain, g., after 1 hr. at			
Fe	Cr	Ni	Al	700°C. (1290°F.)	800°C. (1470°F.)	900°C. (1650°F.)	1000°C. (1830°F.)
100	...	.	..	0.76	5.51	10.00	Destroyed
75	25	..	.	0.58	3.18	7.95	13.2
50	25	25		0.43	3.18	8.07	12.5
75	25	.	10†	0.16	0.70	1.50	6.4
	100	..	..	0.64	1.12	3.29	6.0

* Gruber.(141)

† 10 per cent aluminum was added to an alloy containing 75 per cent iron and 25 per cent chromium

According to MacQuigg,(380)

Sulphur and sulphur gases are without action up to 980°C. (1800°F.) on the high-chromium alloys substantially free from other metals. Laboratory tests have been made in moist mixtures of sulphur dioxide and oxygen for several hours at 980°C. (1800°F.), and after this treatment only light tarnishes appeared on bright metal specimens.

It is evident from the conflicting data on the effect of sulphur-containing gases that further work is urgently needed. It is also evident that the problem is so complex that no general conclusions regarding the resistance in service of high-chromium steels to sulphur-bearing gases should be drawn from laboratory tests unless these simulate closely actual operating conditions; and even then such conclusions should be drawn very tentatively and with great caution.

121. Resistance of High-chromium Steels to Sulphur Vapor.—Scharschu* supplied data on the corrosion in sulphur vapor of low-carbon 25 to 30 per cent chromium steels of the following composition:

No.	Composition, per cent					
	C	Mn	Si	Cr	Ni	Al
55	0.12	....	....	27.60	0.25	
55 Al	0.15	0.81	0.85	25.06	0.72	1.53

Samples were inserted into a porcelain tube in an electric furnace, and sulphur vapor, produced by boiling sulphur in a flask outside the furnace, was passed over the specimens. The test was continued for 24 hr., and the corrosion rate was determined by removing the scale with 10 per cent nitric acid and measuring the reduction in cross-sectional area. The results are given in Table 72.

It will be noted that up to about 870°C. (1600°F.) the steel containing aluminum had a corrosion rate of about twice that of the material containing no aluminum, but above this temperature the corrosion rates of the two steels were approximately the same. In commenting on these data Scharschu stated that neither alloy had good resistance to sulphur vapors at any temperature above the boiling point of sulphur, which was given as 446°C. (835°F.). "In molten sulphur the regular alloy shows better resistance than the aluminum-containing alloy."

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* Private communication. Publication of these data permitted by courtesy of Allegheny Ludlum Steel Corporation.

TABLE 72.—CORROSION OF LOW-CARBON 25 PER CENT CHROMIUM STEEL IN SULPHUR VAPORS*

Steel 55				Steel 55 Al			
Temperature of test		Corrosion		Temperature of test		Corrosion	
°C.	°F.	Penetration, in. per month	Weight loss, mg. per sq. dm. per day	°C.	°F.	Penetration, in. per month	Weight loss, mg. per sq. dm. per day
295	560	0.00075	48.7	295	560	0.0015	97.5
360	680	0.00075	48.7	375	710	0.0015	97.5
455	850	0.0023	149.5	495	925	0.0045	292.5
575	1070	0.0038	247	620	1150	0.006	390
700	1290	0.0085	553	745	1375	0.020	1300
820	1510	0.026	1690	845	1550	0.051	3355
880	1620	0.048	3120	915	1675	0.072	4680
930	1705	0.060	3900	955	1750	0.087	5655
950	1745	0.075	4875	980	1795	0.087	5655
955	1755	0.083	5395	990	1810	0.087	5655

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* Scharschu, private communication.

E. MODIFIED 20 TO 30 PER CENT CHROMIUM STEELS

With the exception of the addition of nitrogen, which has been discussed in this chapter, the composition of the 20 to 30 per cent chromium steels has, in general, remained unchanged since their introduction to industry. The reason for this is obvious; often, the addition of other metals either fails to improve the properties sufficiently to warrant the additional cost, or else some of the existing properties are impaired. For instance, the addition of several per cent molybdenum or tungsten does improve the strength at moderately high temperatures, but at still higher temperatures—1000°C. (1830°F.) or above—the oxidation resistance of the steels is reduced.

122. Effect of Nickel and Molybdenum.—Under some conditions, however, the addition of from 3 to 5 per cent nickel with or without 1 to 1.5 per cent molybdenum has been advantageously used with carbon contents below 0.25 per cent and chromium contents between 25 and 30 per cent. Nickel in these amounts improves toughness, while the molybdenum is added to enhance corrosion resistance. A steel containing both nickel and molybdenum with less than 0.10 per cent carbon was developed in Sweden for use in the paper industry. Unpublished data on a steel of this type, containing 0.08 per cent carbon, 26.32 per cent chromium, 0.18 per cent manganese, 0.64 per cent silicon, 3.77 per cent nickel, and 1.75 per cent molybdenum, showed that it had good corrosion resistance against salt water and nitric acid. The steel also had somewhat better bending properties and in general was tougher than a steel of similar carbon and chromium contents which contained no nickel. Good corrosion resistance of this type of steel in solutions containing 24 and 60 per cent by weight of zinc chloride, heated to 85 to 90°C. (185 to 195°F.), was reported by Kuczynski and Weiss.(283)

123. Effect of Titanium and Columbium.—The effects of titanium and columbium on low-carbon 20 to 30 per cent chromium steels were determined by Becket and Franks(308) and by Tofaute.(477) The former noted that additions of either titanium or columbium in sufficient quantity to combine with the carbon present increased the ductility and made it possible to fully soften the steels in a much shorter heat-treating period than that required for the normal steels without titanium or columbium. Some of their data are shown in Table 73.

TABLE 73.—EFFECT OF TITANIUM ON THE TENSILE PROPERTIES OF 26 PER CENT CHROMIUM STEELS*

Composition, per cent			Heat treatment†	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
C	Cr	Ti						
0.14	26.28	....	1	83,000	56,000	26	51	159
			2	66,000	49,000	5	6	137
0.18	26.90	1.20	1	83,000	57,000	26	56	137
			2	83,000	58,000	28	58	143

* Becket and Franks.(308)

† 1 = heated 12 hr. at 875°C. (1600°F.) and water quenched; 2 = heated 30 min. at 900°C. (1650°F.) and water quenched.

Tofauté(477) found that the low-carbon 25 to 30 per cent chromium steels containing titanium had improved corrosion resistance. His steels, however, contained considerably more titanium than that required to combine with the carbon. The carbon contents of his steels ranged between 0.03 and 0.05 per cent, with titanium between 0.60 and 1.14 per cent.

F. AUTHORS' SUMMARY

1. The 20 to 30 per cent chromium steels are used extensively both as castings and as wrought products. The carbon content of the wrought products, used to resist heat and corrosion, is generally limited to 0.25 per cent maximum. In the case of castings, two carbon ranges are usual; those having a maximum carbon content of 0.35 per cent are employed for resisting corrosion and high-temperature oxidation, whereas those containing between 1 and 3 per cent carbon are used to resist high-temperature oxidation and abrasion. The greater part of the tonnage of the 20 to 30 per cent chromium steels for ingots is melted in the basic-lined electric furnace, but the majority of the castings are produced in acid-lined electric furnaces. The casting practice for ingots follows closely the procedure used for high-carbon tool steels; but the ingots may be larger. It is advisable to use dry sand molds to prevent excessive burning-in of mold material.

2. The 20 to 30 per cent chromium steels with carbon lower than about 0.25 per cent can be hot worked readily. Rods can also be cold drawn to wire. Initial hot-working temperatures are in the neighborhood of 1100°C. (2010°F.), and finishing temperatures should not be greatly below 750°C. (1380°F.). The thermal conductivity of the steels is about 40 per cent of that of ordinary carbon steel, and prior to hot working sufficient time should be allowed for the heat to soak through the section. If the carbon content approaches 0.5 per cent, trouble may be encountered in hot working; and if the carbon content is increased to 1 per cent or more, the material is hot worked with great difficulty. Cold-working properties are adversely affected by high carbon content, and it is advisable to keep the carbon as low as industrially possible when the wrought steels are to be cold worked or drawn.

3. The low-carbon 20 to 30 per cent chromium steels are ferritic under all conditions of heat treatment; their structures consist primarily of chromium ferrite and carbides, which means that the steels are substantially non-hardenable. Large grains present in the cast state can be reduced in size by hot or cold working only.

When the carbon content just exceeds 1 per cent, it is possible to increase the hardness by rapid cooling from about 1000°C. (1830°F.), and as the carbon is raised further to between 2 and 3 per cent, still higher hardness can be obtained by similar heat treatment. With the larger percentages of carbon present, the steels contain numerous large carbide particles. The ductility and softness of the wrought low-carbon steels are improved by heating between 850 and 900°C. (1565 and 1650°F.) for a number of hours, followed by rapid cooling. Cooling should always be rapid to avoid temper brittleness which develops after relatively short exposure to temperatures in the range 400 to 550°C. (750 to 1020°F.). This brittleness exists only after the steels have been cooled to 100°C. (210°F.) or below and can be removed by heating to at least 600°C. (1110°F.) and cooling rapidly. The cause of this phenomenon has been investigated, but as yet no reasonable explanation can be given.

4. In the softened condition, the wrought low-carbon 20 to 30 per cent chromium steels have a tensile strength of about 85,000 lb. per sq. in. and an elongation in 2 in. of about 30 per cent, but their notch impact strength is low. The endurance limit is about one-half the tensile strength, and the corrosion endurance is high. These steels are machinable and can be welded, riveted, brazed, soldered, or otherwise joined. However, the welds are not sufficiently ductile for use under all conditions, since grain growth occurs in adjacent regions during the welding operation. Whenever possible, the welded structures should be annealed.

5. Castings of either the low- or high-carbon 20 to 30 per cent chromium steels have low ductility, although their tensile strength is somewhat above that of ordinary cast steel. The annealing treatment to be employed on cast steels containing up to 0.35 per cent carbon consists of holding for an extended period at about 900°C. (1650°F.) followed by slow cooling to about 650°C. (1200°F.) and subsequent rapid cooling to normal temperatures. This treatment does not produce a refinement in grain structure but does remove casting strains. After this treatment, the castings can be machined with difficulty and are in the best condition for resisting heat or corrosion. Castings containing from 1 to 3 per cent carbon are hardened (to 500 Brinell) by heating to temperatures of about 950°C. (1740°F.) and

cooling rapidly. Such castings can be softened for machining by holding for 6 to 12 hr. at 750°C. (1380°F.) followed by either furnace or air cooling.

6. The coefficient of linear expansion of the 20 to 30 per cent chromium steels is about the same as that of carbon steels. The electric resistivity of the low-carbon steels increases with the chromium content. Density decreases with the chromium content.

7. The short-time elevated-temperature tensile strength of the low-carbon steels decreases with temperature, from about 85,000 lb. per sq. in. at room temperature to about 6000 lb. per sq. in. at 1000°C. (1830°F.). Creep stresses for 1 per cent elongation in 10,000 hr., while probably somewhat higher than those for unalloyed low-carbon steels, are much below those for 18-8 and other high chromium-nickel austenitic alloys or for high-speed steel. Creep data for the 20 to 30 per cent chromium steels are erratic and conflicting.

8. The 20 to 30 per cent chromium steels are resistant to oxidation at elevated temperatures and to oxidizing media at atmospheric temperatures. The carbon content does not greatly influence the oxidation resistance of the steels, but does detrimentally affect their corrosion resistance. While the high- as well as the low-carbon steels resist oxidation satisfactorily at temperatures up to approximately 1150°C. (2100°F.), greatest resistance to corrosion requires that the carbon content should not exceed one one-hundredth of the chromium content. The low-carbon steels are suitable for resisting oxidizing solutions, such as mine waters containing sulphuric acid and sulphates, or mixtures of nitric and other acids, so long as the nitric acid concentration is sufficient to render the surface of the steels passive. Even the low-carbon steels, however, are unsuitable for resisting sulphuric or hydrochloric acid and others which destroy or retard passivation.

9. The 20 to 30 per cent chromium steels have been used as furnace parts, rabble arms, recuperator parts, baffles, kiln linings, glass molds, and tube supports that operate at high temperatures. The steels are not so strong as the austenitic chromium-nickel steels but are more resistant to gases containing sulphur compounds. High- and low-carbon castings are used in ore-roasting furnaces and as auxiliary equipment if sulphur compounds are

present. The high-carbon castings withstand abrasion both at normal and at elevated temperatures, as well as the sulphur attack, which is even more greatly retarded by the cast low-carbon steels. Plates of the high-carbon steels are used in pan mills for grinding abrasives and in heating furnaces to resist both wear and oxidation. However, under strongly carbonizing conditions castings, or even wrought products, of these steels will pick up carbon and become very brittle.

10. While the effects of numerous additional alloying elements on the 20 to 30 per cent chromium steels have been determined, with one exception the composition of the bulk of wrought steels made for commercial consumption has remained practically unchanged since their introduction to commerce. Investigations in this country and in England have indicated that nitrogen, in the form of ferrochromium containing nitrogen, when added to the extent of about 0.15 to 0.25 per cent, causes a reduction in the grain size of the cast metal and assists in the prevention of grain growth in the wrought products. It increases ductility during hot working because the grain size of the cast ingots is reduced, which makes it possible to bloom large ingots of the steels without prior forging. Nitrogen apparently increases the impact resistance of the wrought steels, facilitates cold-drawing operations, and restrains the grain growth that occurs in the normal steels in the zones adjacent to welds. Several per cent nickel with or without about 1.5 per cent molybdenum have been added to the 25 per cent chromium steels, and small quantities of such modified steels have been used for special purposes. Their chief use has been in resisting corrosion at normal temperatures.

CHAPTER VIII

CHROMIUM CAST IRON CONTAINING 12 TO 35 PER CENT CHROMIUM

General Characteristics of High-chromium Cast Irons—Effect of Heat Treatment—Special Properties—Composition and Application—Authors' Summary

In view of the corrosion and oxidation resistance of steels and low-carbon irons containing 12 per cent or more chromium, it is natural that attempts were made to produce oxidation- and corrosion-resistant cast irons of high chromium content. Such irons have been found to possess useful properties; however, their production is still limited, and much of the information on them has necessarily been drawn from laboratory reports and correspondence. The high-chromium cast irons differ from the lower carbon high-chromium steels and irons in that there is eutectic formation on solidification, a characteristic of cast irons. The eutectic, often called "ledeburite," appears in high-chromium alloys of relatively low carbon content due to reduction in carbon solubility which accompanies rising chromium content. The work of Valenta(166) and of Oberhoffer, Daeves, and Rapatz,(52) for example, has established the fact that from the point of view of the iron-carbon diagram a 20 per cent chromium alloy with more than 0.6 per cent carbon should be classified as a white cast iron and not as a steel. However, as mentioned in the previous chapter, there is in practice considerable confusion in nomenclature; for example, alloys that should, strictly speaking, be called "cast irons" are commonly known as "high-chromium steels." This made classification of the data difficult, particularly if the carbon content was below 3 per cent. This is discussed in the previous chapter (page 173).

High-chromium cast irons containing 12 to 35 per cent chromium have been produced at various times in cupolas, electric furnaces, and air furnaces. In general, the maximum chromium content of cupola iron approximates 20 per cent. When it is desired to increase the chromium above this figure, recourse is usually had to other melting units, such as electric or air furnaces or the newer types of pulverized-fuel furnaces. In the cupola, chromium may be added either as lump ferrochromium or in the form of chromium briquettes. However, appreciable oxidation loss and excessive carbon pickup are likely to occur if lump ferrochromium is employed in this type of melting unit and, in practice, the use of briquetted chromium has been found most convenient, particularly as the protection furnished the chromium by the binder limits oxidation and tends to inhibit excessive increase in carbon content. Even with the use of chromium briquettes it is difficult to obtain carbon contents under 3.5 per cent in high-chromium iron owing to the rapid reaction of carbon and chromium. Recent developments directed toward lowering the carbon content in cupola iron consist of the addition, either in lump or in briquette form, of a ferrochromium containing about 2 per cent carbon and appreciable percentages of silicon and copper. By the use of this addition to the charge, together with a high percentage of steel scrap, 15 per cent chromium irons containing under 3 per cent carbon have been produced in the cupola.

In comparison with unalloyed cast irons, the high-chromium cast irons generally appear cold or dull in the ladle and during pouring. This is not due to the same conditions as in unalloyed iron, but rather to the formation of a surface film. Despite this appearance, the high-chromium cast iron retains its fluidity and is readily cast into intricate shapes. The average shrinkage is 1.8 per cent. As the irons are characteristically white, suitable alterations of gates and risers are made. Because of the possibility of heat cracking, abrupt changes in section and sharp corners are avoided.

A. GENERAL CHARACTERISTICS OF HIGH-CHROMIUM CAST IRONS

The starting point of the study of high-chromium cast iron is the iron-chromium-carbon diagram, which is reviewed in detail in Volume I, Chapter III. Extension to the effect of silicon was attempted by Pobořil,(484) who constructed sections at 2.5 per cent silicon and 0.8 per cent carbon and at 2.5 per cent silicon and 25 per cent chromium; these are shown in Figs. 60 and 61.

In the absence of detailed information, these may be used as rough guides. As a further aid to the discussion of high-chromium cast irons, a somewhat simplified version of the ordinary-temperature section of the iron-chromium-carbon diagram is given in Fig. 62; the hatched portion indicates roughly the composition ranges of eutectic behavior at elevated temperatures. The boundaries shown are displaced by the amount of silicon ordinarily found in these cast irons, but reliable quantitative data are wanting.

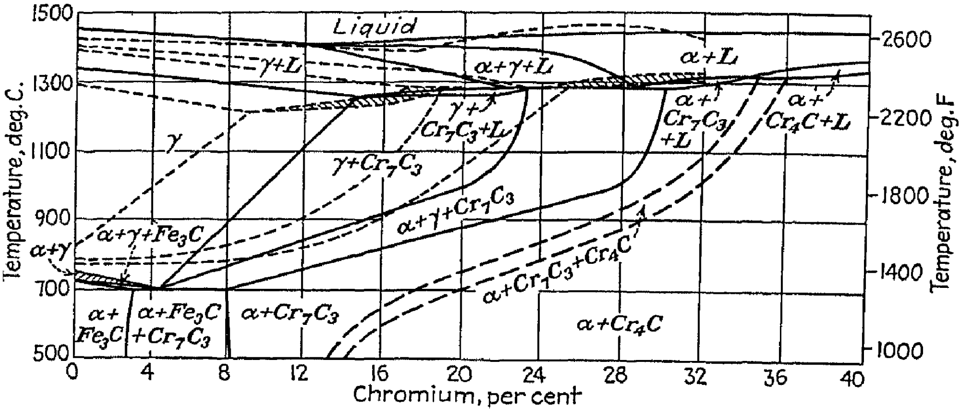

FIG. 60.—Effect of silicon on iron-chromium-carbon alloys. Section of the ternary diagram at 0.8 per cent carbon. (*Pobořil.*[434])

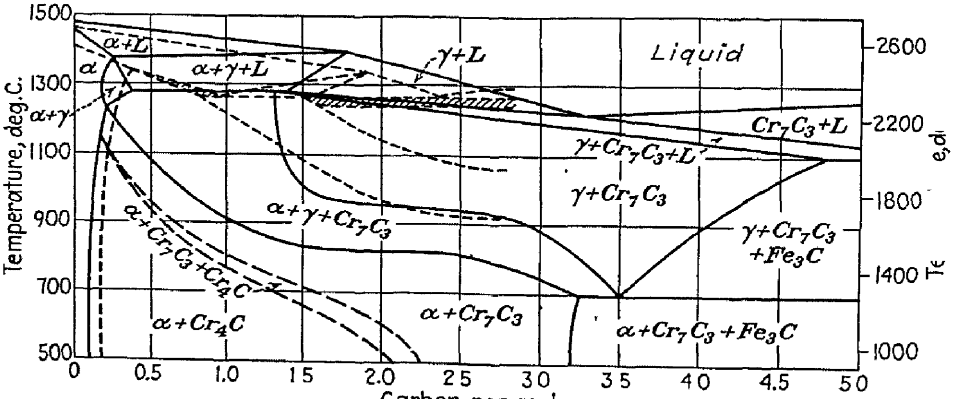

FIG. 61.—Effect of silicon on iron-chromium-carbon alloys. Section of the ternary diagram at 25 per cent chromium. (*Pobořil.*[434])

124. Effect of Chromium.—When chromium is added to a cast iron containing 2.0 to 3.5 per cent carbon and 1.5 to 2.75 per cent silicon, the iron gradually becomes white and its hardness progressively increases until the chromium reaches approximately 5 per cent. The hardness then remains substantially constant, and the iron is not machinable with the usual cutting tools until the chromium exceeds about 10 per cent, when a slight but definite lowering in the Brinell hardness is evident.

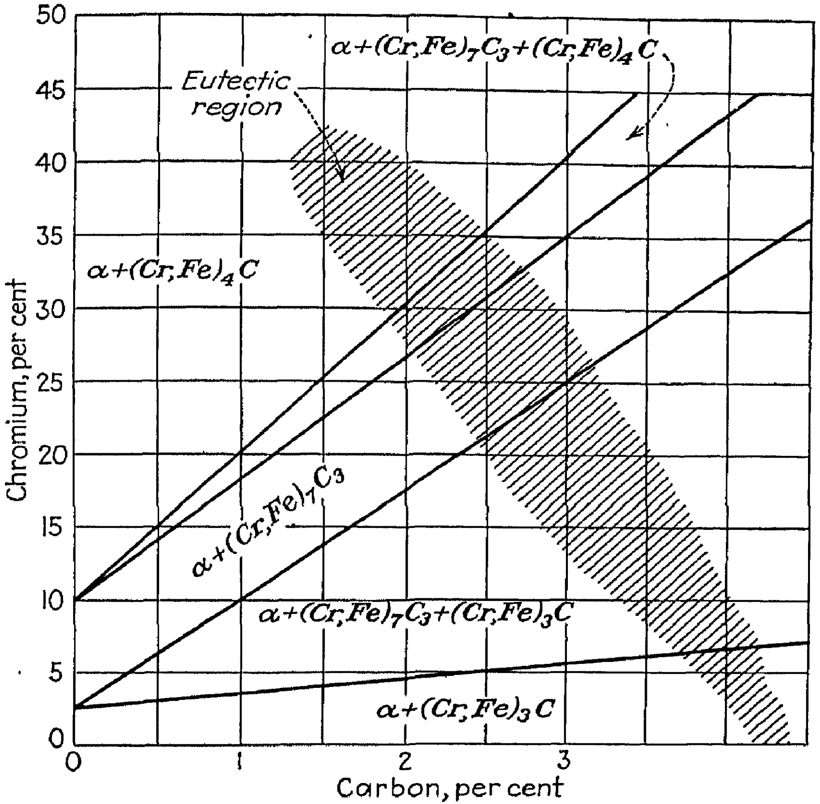

FIG 62.—Simplified section of the iron-chromium-carbon diagram at room temperature.

This lowering in hardness of high-carbon irons, sand cast in the form of standard A.S.T.M. arbitration bars, is shown in Fig. 63, together with curves illustrating transverse strength and deflection on 12-in. centers. The large number of irons from which the data for these curves were obtained contained 2.5 to 3.15 per cent carbon and 1.75 to 2.5 per cent silicon. The use of irons with a maximum carbon content of 2.5 per cent would, of course, increase the transverse and deflection values considerably. Confirmation of hardness decrease with increase of chromium is found in data obtained by Taniguchi(297) on the hardness of chilled irons containing approximately 3.15 per cent carbon and 0.55 per cent silicon. He noted that an increase in hardness accompanies an increase in chromium content from 5 to 9 per cent. In his tests the hardness began to drop as the chromium reached 12 per cent, and a minimum was shown with a chromium content of approximately 18 per cent. Although this drop in hardness may be relatively slight, as noted in Fig. 63, the high-chromium cast irons show a considerable increase in strength and some increase in deflection at this point. If the carbon content does not exceed approximately 3 per cent, these irons are machinable when the chromium content reaches approximately 13 per cent. That cast irons of this analysis are machinable is remarkable, as their hardness frequently exceeds 400 Brinell. However, cast irons of this type containing up to 3 per cent carbon, produced on either a laboratory or a commercial scale, have been successfully machined and threaded with high-speed steel tool bits. Although commercially machinable, they are not so readily turned or drilled as ordinary gray irons and require considerably lower spindle speeds. Occasionally they have a relatively hard skin or coat, which is removed by an initial heavy cut.

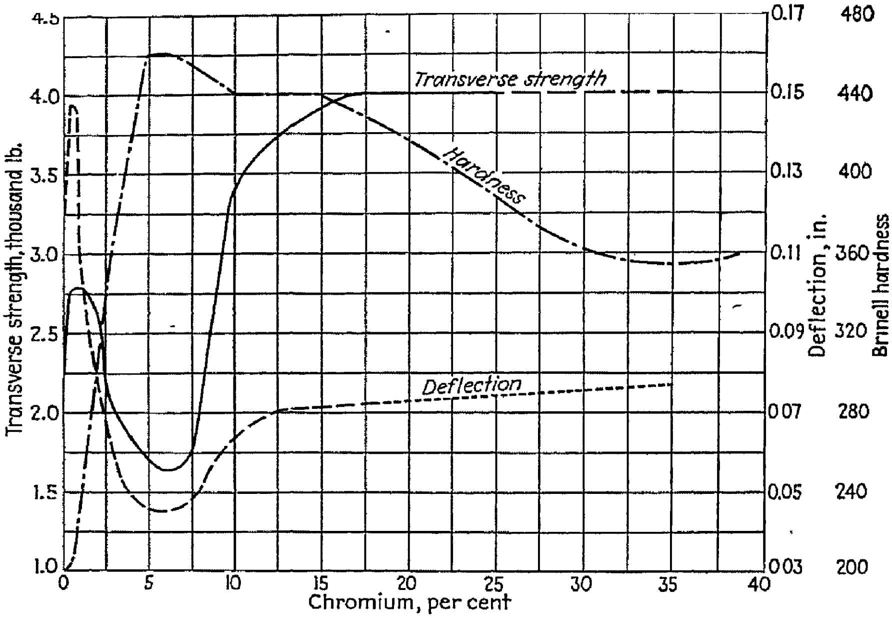

FIG. 63.—Effect of chromium on the mechanical properties of cast iron containing 2.5 to 3.15 per cent carbon and 1.75 to 2.5 per cent silicon.

This technique of machining by a heavy cut at comparatively low speed has been found advisable through a wide range of chromium contents.(182) It is undoubtedly necessary owing to the work-hardening character of these cast irons.

Metallographic examination of the irons reveals the fact that, if the carbon content is held constant, a refinement in the coarse needles and crystals of carbide occurs as this hardness-inflection point is reached and exceeded. This is due to two factors. First, the trigonal type of carbide becomes predominant, as may be seen from Fig. 62. It will be noted from this diagram that, as chromium in a cast iron containing 2.5 per cent carbon approaches 15 per cent, the carbide type becomes predominantly trigonal, $(Fe,Cr)_7C_3$, instead of orthorhombic, $(Fe,Cr)_3C$. This trigonal carbide is equidimensional rather than of the needle-like form typical of cementite. This behavior is accentuated by the presence of silicon, owing to the fact that silicon acts to precipitate the carbides at a higher temperature; and with a given chromium content the carbides in equilibrium at higher temperatures in this range are predominantly of the trigonal type. The exact displacement of the line has not been determined but appears to be 3 per cent chromium at 2.5 per cent silicon; *i.e.*, with 2.5 per cent silicon and 2.5 per cent carbon, this line would pass through 18 per cent chromium rather than 21 per cent as shown in Fig. 62. The marked refinement in the structure is also due to the fact that fine carbides of the eutectic type develop when the chromium content increases to about 15 per cent in a 2.5 to 3.15 per cent carbon iron, and these fine carbides replace the long needles of the type found in lower chromium irons and ordinary white iron. It may be seen in Fig. 62 that iron-chromium-carbon alloys containing approximately 2.75 to 3 per cent carbon and 12 to 15 per cent chromium lie within the eutectic region. The marked difference in structure between a normal white iron or a lower chromium cast iron and one containing 12.86 per cent chromium is shown in Fig. 64. A similar type of structure in an iron containing approximately 3 per cent carbon, 20 per cent chromium, and 1 per cent silicon has also been noted by Valenta.(166) Further increase, up to 25 per cent, in chromium content of the irons has no marked effect on the structural appearance of the carbide except for an accentuation of the trigonal form of the carbides. This would be expected from the position of the carbide fields in Fig. 62 and the fact that, with higher chromium, irons in this carbon range tend to be slightly hypereutectic, which facilitates the separation of carbides.

In actual practice, use has been made of chromium additions of approximately 9 per cent.(293) In this case, as may be seen from Fig. 62, it is necessary to drop the carbon content to approximately 1 to 2 per cent to ensure the predominant production of trigonal carbides. Irons of this analysis show considerable heat resistance but are inferior in this regard to the higher chromium cast irons.

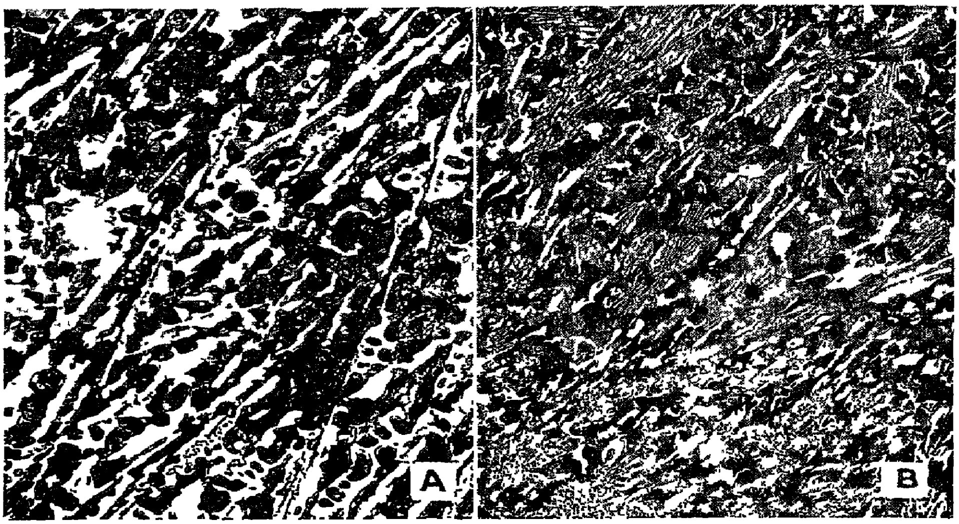

FIG. 64.—Structure of cast irons containing (*A*) 5.18 per cent chromium and (*B*) 12.86 per cent chromium Both cast irons were of the same basic composition 100×.

125. Effect of Carbon.—In addition to the necessity of obtaining the correct chromium content, it has been found that the carbon content has a marked effect on the structure and the mechanical properties of alloy cast irons. The structure of cupola irons containing 14.80 per cent chromium with 3.75 per cent carbon, and 14.40 per cent chromium with 2.77 per cent carbon respectively is illustrated in Fig. 65. It is evident that, as the carbon drops to 3 per cent or below, *i.e.*, as the eutectic zone is reached with a 2.5 per cent silicon content, a very marked refinement in structure takes place with elimination of large crystals of hypereutectic carbide. The accompanying improvement in properties is illustrated by the first two irons in Table 74. The data for the air-furnace irons, with somewhat higher chromium content, indicate that some gain in deflection and tensile strength is obtained by raising the chromium content to 17 per cent. Also included in Table 74 are the properties of two lower carbon electric-furnace irons containing approximately 24 per cent chromium, as determined by Phillips.(332) The improvement, particularly in deflection, with lower carbon contents is evident. Although the field has not been covered thoroughly, it appears, as illustrated in Fig. 63, that with a constant carbon content of over 2.5 per cent, increase in chromium from 18 per cent to approximately 35 per cent does not greatly improve the strength and deflection. However, improvement is obtained in other properties, *e.g.*, oxidation resistance and suppression of volume changes; this is discussed in a subsequent section.

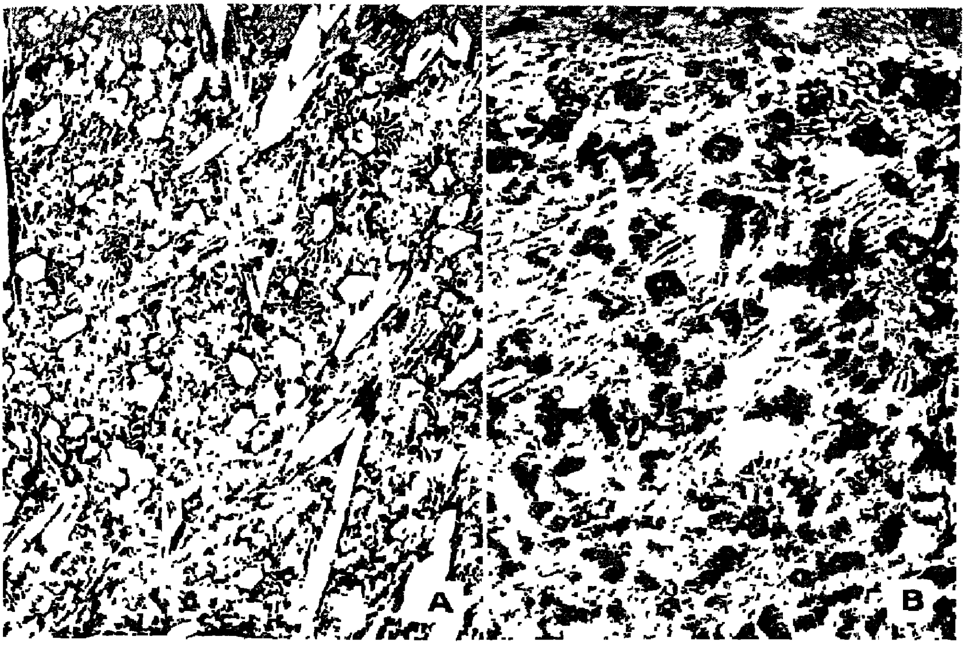

FIG. 65.—Structure of 15 per cent chromium cast irons containing (*A*) 3.75 per cent carbon and (*B*) 2.77 per cent carbon. Note the refinement of carbides accompanying the lower carbon. 100 ×.

It may also be noted that, despite elimination of the gamma phase by high chromium content, the hardness of such high-

TABLE 74.—EFFECT OF CARBON ON THE PROPERTIES OF HIGH-CHROMIUM CAST IRONS

Investigator	Type of iron	Composition, per cent			Transverse properties				Tensile strength, lb. per sq. in.	Brinell hardness	Remarks
					18-in. span		12-in. span				
		C	Si	Cr	Transverse strength, lb.	Deflection, in.	Transverse strength, lb.	Deflection, in.			
Union Carbide and Carbon Research Laboratories, Inc.	Cupola	3.75	2.56	14.80	2400	0.095	2650	0.053	31,100	464	Unmachinable
	Cupola	2.77	2.44	14.40	3600	0.143	4630	0.068	48,900	444	Machinable
	Air furnace	2.86	1.81	17.00	....	.....	4000	0.11	53,900	444	Machinable
	Air furnace	2.18	1.67	17.50	....	.....	6000	0.13	75,900	415	Machinable
Phillips(332)..........	Electric furnace	1.54	1.18	24.70	4670	0.23	...	.....	73,800	363	
	Electric furnace	1.84	1.96	23.95	4285	0.19	....	...	85,600	341	

carbon alloys (over 2.5 per cent carbon) does not ordinarily fall below approximately 350 Brinell.

As stated previously, the data in the literature on the exact effect of carbon on the mechanical properties are few and frequently contradictory. However, for transverse bars tested on 12-in. centers and for cast-iron tensile specimens, the approximate trend of properties with carbon in 15 to 17 per cent chromium, 1.5 to 2.5 per cent silicon cast irons is shown in Fig. 66. The

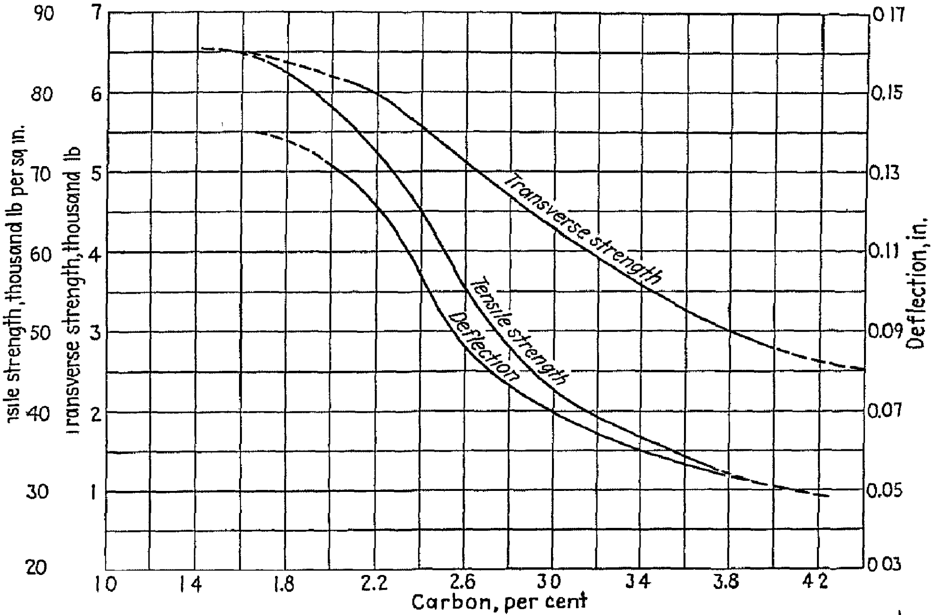

FIG. 66.—Effect of carbon on the mechanical properties of 15 to 17 per cent chromium cast irons.

effect of higher chromium content is in general to decrease the slope of the transverse- and tensile-strength lines by decreasing the strength at low carbon contents and increasing somewhat the strength at high carbon contents, at least up to 3 per cent carbon.

Considering the effects of chromium and carbon described in the foregoing, tentative conclusions can be drawn on their proper proportioning for best mechanical properties. It appears that the strength properties of a chromium cast iron are usually satisfactory until the eutectic percentage of carbon is exceeded. When the carbon content is sufficient, however, to exceed that of the eutectic zone shown in Fig. 62, a distinct loss of strength results, presumably owing to the separation of large crystallites of hypereutectic carbide. Unpublished experiments have shown a hypereutectic structure appearing in a 17.5 per cent chromium, 1.75 per cent silicon cast iron when the carbon reached 3.5 per cent, and in a 25 per cent chromium, 1.75 per cent silicon cast iron when the carbon reached 3 per cent. Thyssen(512) recently reported transverse properties of a number of high-chromium cast irons containing approximately 1 per cent silicon which appear to confirm this observation. If his transverse-strength values for an approximately constant chromium content are plotted against carbon content, a drop in strength is evident as the carbon content reaches 3.15 per cent in 15 to 20 per cent chromium cast irons, 2.8 per cent in 22 to 29 per cent chromium cast irons, and 2.25 per cent in 32 to 39 per cent chromium cast irons. Deflection decreases in a rather uniform manner with carbon content until the eutectic percentage is exceeded, at which point the deflection also sharply decreases.

The location of the eutectic region can be observed frequently by examination of fractured test pieces. For example, if chromium is added to a 3 per cent carbon, 2 per cent silicon iron, the usual white-iron fracture becomes noticeably finer as the chromium reaches approximately 8 per cent and remains fine up to a chromium content of 18 per cent. If the chromium is further increased to 25 per cent, the fractured surface exhibits prominent needles typical of hypereutectic chromium cast iron.

126. Effect of Silicon.—Silicon is generally added to high-chromium cast irons in quantities varying from 1 to 3 per cent. The chief effects from its addition are as follows:

1. It increases the oxidation and corrosion resistance.
2. It dissolves in the iron and refines the carbides in irons with less than the eutectic percentage of carbon,(166) but it is not responsible, at least up to 3 per cent,(302) for the formation of any special structural constituent.
3. It prevents excessive air hardening of the solid-solution groundmass. This is brought about because silicon lowers the solubility of carbon in the groundmass and, therefore, throws carbides out of solution at high temperatures. For example, Valenta(166) concluded that air hardening on cooling from 1000°C. (1830°F.) is suppressed by 2.3 to 2.5 per cent silicon in 15 per cent chromium alloys containing as much as 1 per cent carbon, and in

35 per cent chromium alloys containing as much as 3.5 per cent carbon. On the other hand, with low-silicon alloys air hardening takes place if the carbon content of the 15 per cent chromium alloys exceeds 0.5 per cent or if the carbon content of the 35 per cent chromium alloys exceeds 2 per cent. Silicon raises the whole

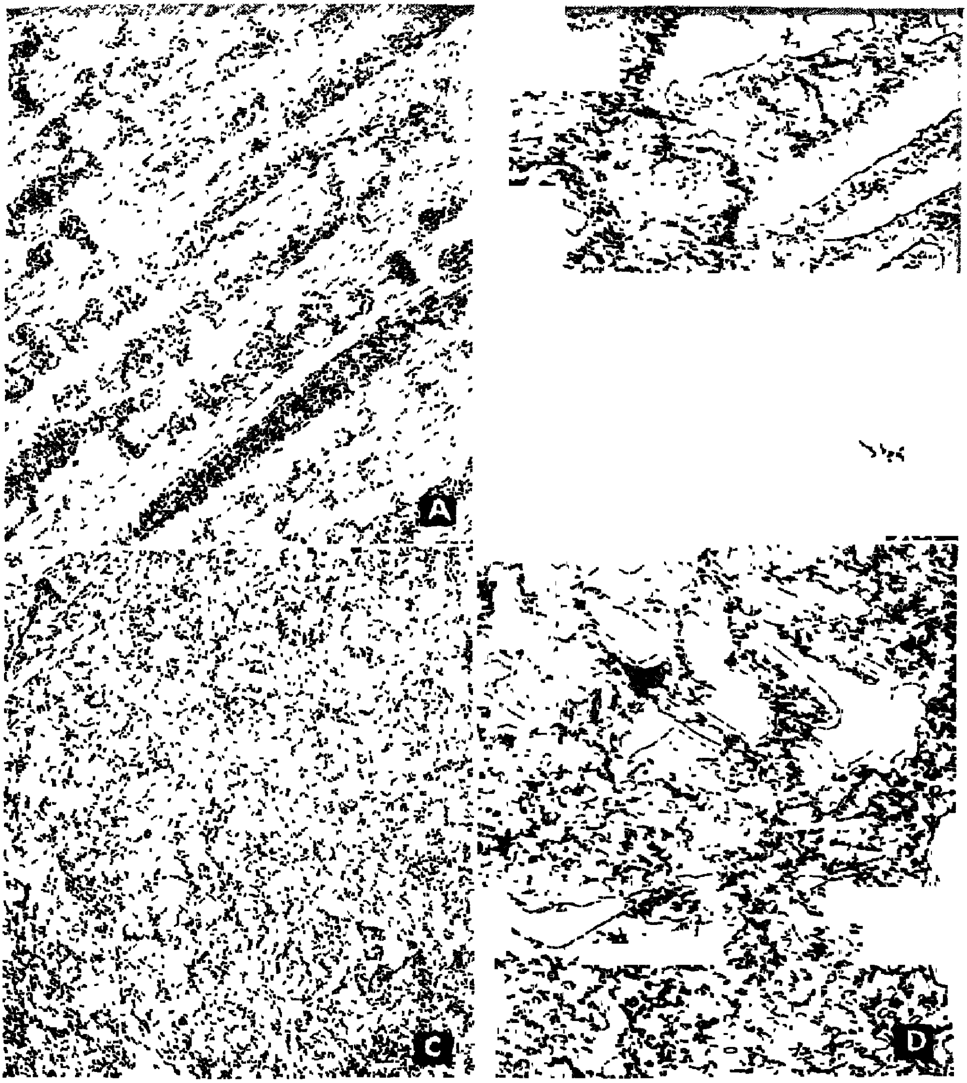

Fig. 67.—Structure of cast irons containing 2.32 per cent carbon and 25.16 per cent chromium. (*A*) 0.21 per cent silicon, 100 ×; (*B*) same, but 500 ×; (*C*) 1.98 per cent silicon, 100 ×; (*D*) same, but 500 ×. Note the refinement of carbides and greater divorce of cementite in the higher silicon iron.

transformation range, causing the gamma-alpha transformation to occur at higher temperatures.

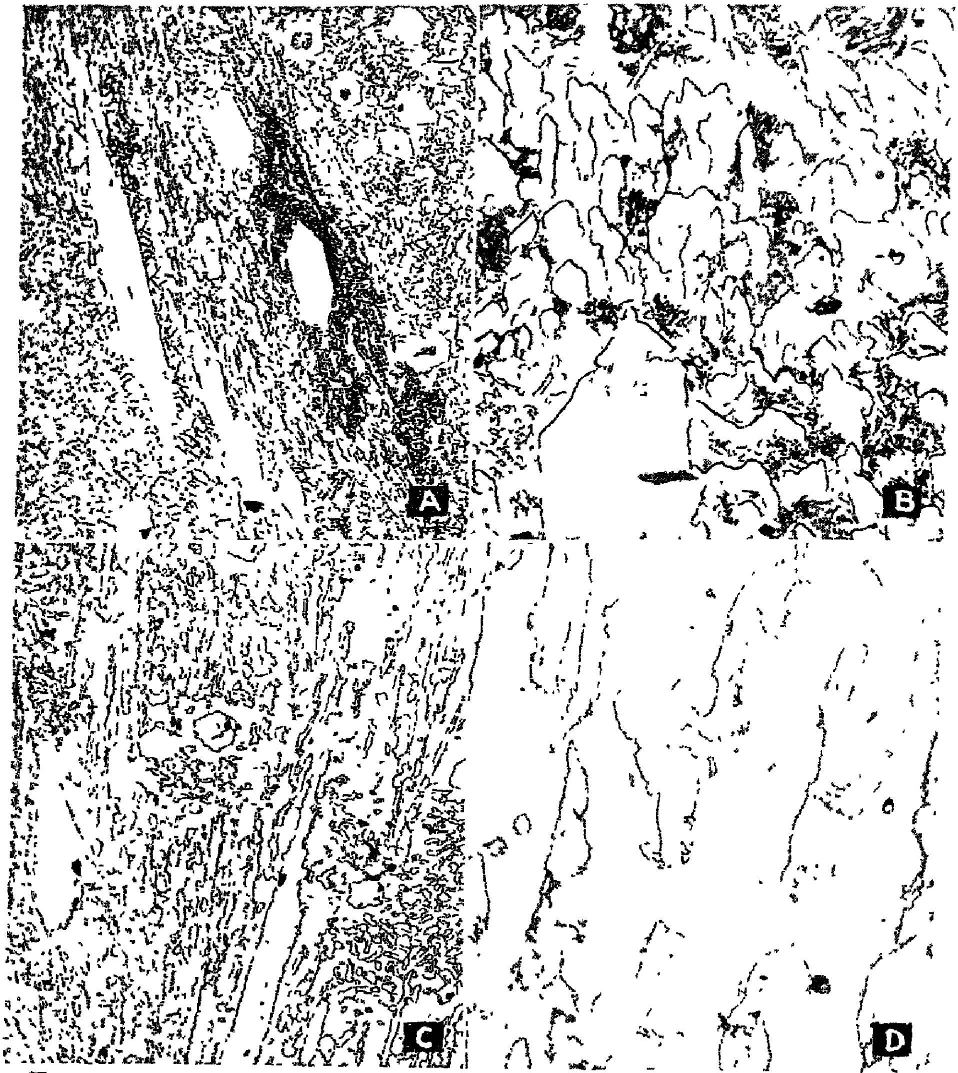

FIG. 68.—Structure of cast iron containing 2.83 per cent carbon and 33.27 per cent chromium. (*A*) 0.56 per cent silicon, 100 ×; (*B*) same, but 500 ×; (*C*) 1.98 per cent silicon, 100 ×; (*D*) same, but 500 ×. Note how silicon produces completely ferritic groundmass.

4. Silicon tends to prevent or minimize dimensional changes and possible cracking from this cause either by raising the transformation range above the temperature at which the iron is

to be used or by decreasing the magnitude of the changes and increasing the temperature at which they take place, to a point at which the iron is sufficiently plastic to yield without cracking. The effect of a silicon increase from 0.21 to 1.98 per cent on 25 per cent chromium cast irons is shown in Fig. 67. The elimination of long continuous carbide areas and the production of a more homogeneous structure, as well as the more complete divorcement of carbide, are evident. A similar effect is noted in alloys containing 17 per cent chromium.

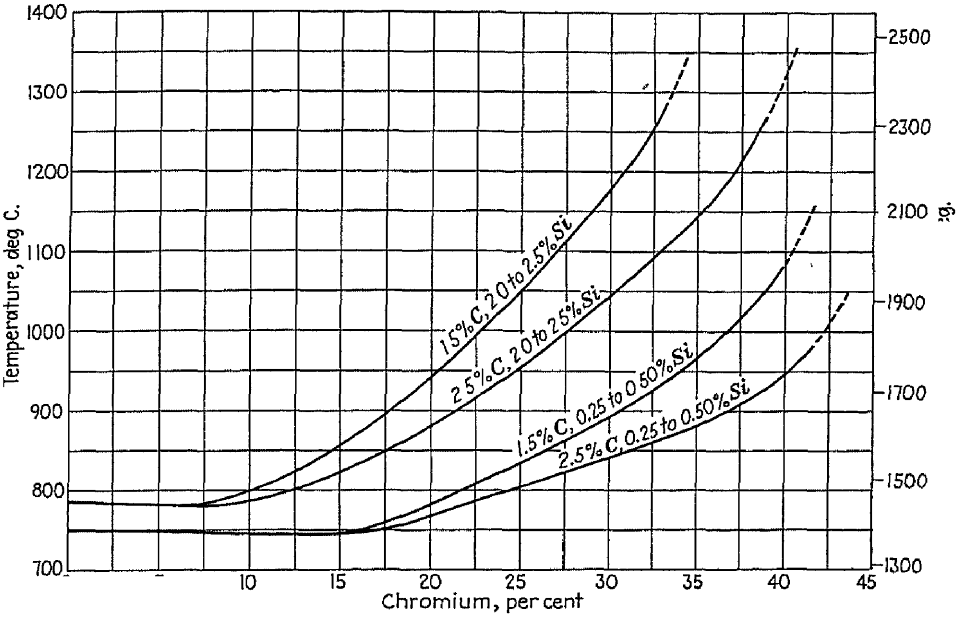

FIG. 69.—Approximate effect of silicon on the alpha-gamma transformation of high-chromium cast iron.

The photomicrographs of higher chromium alloys in Fig. 68 illustrate the effect of silicon of limiting the gamma-phase region. The high-silicon alloy (*C*) shows no evidence of carbide solution in the groundmass, while the lower silicon cast iron (*A*) shows some, recognizable by precipitation markings in the groundmass. With chromium and carbon in these amounts, silicon apparently does not appreciably affect refinement of primary carbides owing to the fact that the eutectic carbon percentage is exceeded.

5. Each 1 per cent silicon increases the hardness of the groundmass of annealed iron approximately 25 Brinell numbers(166); and silicon lowers the carbon content of the eutectic.

The curves of Fig. 69 indicate that the addition of 2 to 2.5 per cent silicon is sufficient to cause substantial increase in the temperature that must be exceeded in order that gamma phase may appear. (In the high-chromium cast irons, however, this at most means a partial share of gamma phase in a polyphase field.) Stated in another way, silicon decreases the amount of chromium necessary to prevent the appearance of gamma phase at any temperature.

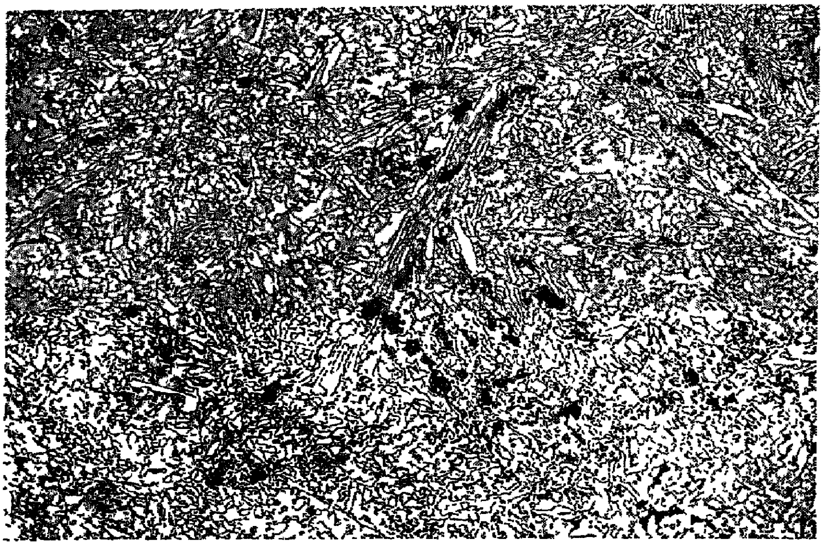

FIG. 70.—Structure of cast iron containing 2.33 per cent carbon, 14.75 per cent chromium, and 4.43 per cent silicon. Note brittle silicon-chromium ferrite groundmass because of high silicon. 100 X.

Despite considerable work by Valenta,(166) Valenta and Pobořil,(302) Houdremont and Wasmuht,(182) and others, there is still considerable uncertainty about the position of the various solubility surfaces.

Increase of silicon above a certain point is inadvisable. Unpublished thermal-shock tests on 17.5 per cent chromium cast irons containing 1 to 3 per cent carbon and 1 to 3 per cent silicon showed that tendency toward cracking on water quenching increases in irons with over 2 per cent carbon when the silicon is increased from 2 to 2.5 per cent. Even under less severe thermal stress the maximum silicon should probably be limited to 3 per cent because, as it approaches 4 per cent, the groundmass of the irons becomes hard and unmachinable, and the irons suffer a drop in strength and loss of ductility.(166) The formation of a groundmass of silicon-chromium ferrite is clearly evident in the photomicrograph of Fig. 70.

127. Effect of Aluminum and Other Alloying Elements.—Only a limited amount of experimental work has been done on the effect of other alloying elements on the properties of high-chromium irons containing over 1.5 per cent carbon. Valenta(166) reported a few tests on chromium-aluminum cast irons; he found 0.5 per cent *aluminum* effective in suppressing air hardening in alloys containing 19.35 to 29.75 per cent chromium with up to 2 per cent carbon. According to his results, aluminum was approximately twice as effective as silicon in raising the critical points. He concluded that in contradistinction to the effect of silicon, the permissible carbon content can be raised without danger of rendering the chromium-aluminum cast irons exceedingly hard and brittle owing to a high proportion of hypereutectic carbides.

Despite these findings, commercial application of aluminum additions to high-chromium cast irons seems to have been rare. In a few unpublished experiments with alloys containing 2.5 to 3.5 per cent carbon and 15 to 25 per cent chromium and aluminum additions of 1 to 3 per cent, it was found that aluminum did not appreciably improve the transverse properties of these high-carbon irons as cast, and as the aluminum reached 3 per cent the irons became weak and brittle. Adverse effects of large aluminum additions on the casting properties may further limit its application in high-carbon irons.

Molybdenum has been added to high-chromium cast irons in quantities up to 3.5 per cent. It has little effect on mechanical properties but induces a considerable amount of coring in the casting. In lower carbon alloys, molybdenum produces increased corrosion resistance to sulphuric and sulphurous acids and sulphite solutions.

The addition of 0.25 to 0.4 per cent *titanium* has been reported by Pobořil(434) to reduce the primary grain size in alloys low enough in carbon and high enough in chromium to be coarse grained as cast and free from transformations in the solid state. Phillips(332) reported a similar effect from the use of *nitrogen*-bearing ferrochromium. Irons containing a maximum of about 1 per cent carbon, a minimum of about 25 per cent chromium, and 1.5 per cent silicon are typical of this class of alloy. Considerably less effect would be expected from such additions to irons higher in carbon or lower in chromium.

Little information is available on the use of small percentages of nickel, copper, and other alloys in high-carbon high-chromium cast irons. Additions of up to 2.5 per cent *nickel* have been made to high-chromium cast irons with very high carbon contents (over 3.5 per cent carbon) without appreciable effect on the transverse properties. *Copper* in amounts up to approximately 2 per cent has been found to exert a slight improvement in the transverse properties of iron containing 15 to 25 per cent chromium and less than 3 per cent carbon. Small additions of up to 0.25 per cent *vanadium, titanium,* or *zirconium* have been made to high-carbon irons (over 3.5 per cent), but insufficient information is available to gage accurately the effect of such additions. Significant results may be obtained in future experimentation with small amounts of these auxiliary additions, but marked effects on the mechanical properties probably will be limited to irons containing a maximum of approximately 2.5 per cent carbon. With the higher carbon alloys the chief difficulty associated with alteration in their properties through such additions is that structurally the irons contain a large percentage of chromium carbides and, consequently, such changes in the groundmass as might be brought about result in only a minor effect on the properties.

B. EFFECT OF HEAT TREATMENT

As may be noted from the preceding discussion and from considerations of oxidation and corrosion resistance, the industrial high-chromium cast irons contain from 15 to 35 per cent chromium. Those designed mainly for oxidation resistance and moderate corrosion resistance lie in the range of 15 to 25 per cent chromium, while those designed specifically for high corrosion resistance lie in the range of 25 to 35 per cent chromium. In addition, these alloy irons generally contain 1 to 3 per cent silicon. The carbon content is preferably less than 3 per cent and ranges down to approximately 1 per cent, improved mechanical properties being obtained in proportion to the decrease in carbon to this point (Fig. 66, page 237).

128. General Heat-treatment and Hot-working Characteristics of High-chromium Cast Irons.—One of the advantages of the high-chromium cast irons with over 1.5 per cent carbon is their relative immunity to structural decomposition at high temperatures. This same property renders them relatively unresponsive to heat treatment. The large crystals or plates of primary iron-chromium carbides or chromium carbides in alloys containing 2 per cent or more carbon are in fact extremely resistant to solution, coalescence, or spheroidization at normal heat-treating conditions of time and temperature. Only a very limited rounding of such carbides is evident on prolonged treatments at temperatures above 1000°C. (1830°F.). The size of the primary carbide crystals and their orientation can be controlled to some degree by varying the casting practice and the section size of the irons. In considering methods of refining this primary carbide structure it has been found that, as in the case of high-carbon high-chromium steels of the 2 per cent carbon, 12 per cent chromium variety, large chromium additions permit the hot working of a high-carbon iron that in the absence of chromium would break up under the hammer or in the rolls. Figure 71 illustrates the great refinement accomplished by such working in the primary carbides of a chill-cast iron containing 2.97 per cent carbon, 12.25 per cent chromium, and approximately 2 per cent

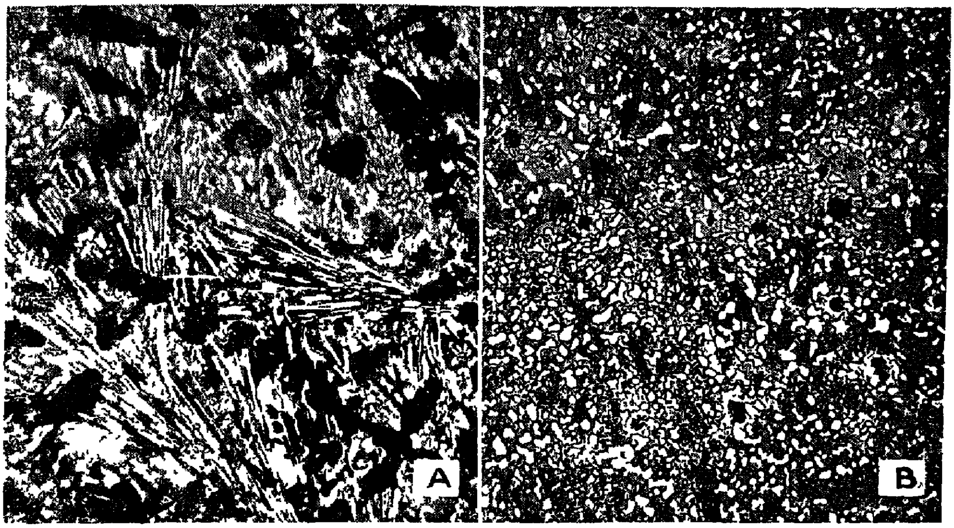

FIG. 71.—Structure of cast iron containing 2.97 per cent carbon, 2 per cent silicon, and 12.25 per cent chromium, (*A*) as cast and (*B*) reduced 40 per cent by hot forging. 100 ×.

silicon. It was possible in this case to reduce the iron 40 per cent under the hammer at a temperature between 850 and 950°C. (1560 and 1740°F.). A drop from 418 to 360 in Brinell hardness was noted. The hot malleability of this iron is the more remarkable considering that the base iron was sufficiently high in phosphorus and sulphur to introduce approximately 0.60 per cent and 0.05 per cent respectively of these two elements into the cast iron. The present information, insufficient as it is, makes the hot working of the high-chromium cast irons of more than theoretical interest.

Carbides in the groundmass, as distinguished from primary carbides, can be successfully dissolved, precipitated, and spheroidized by heat treatment. With sufficient time, complete spheroidization of these carbides and conversion of the groundmass to a ferritic state are obtained at temperatures as low as 800°C. (1470°F.). Higher annealing temperatures increase the rate of spheroidization, the maximum practicable spheroidization temperature naturally being governed by the transformation temperature (Fig. 69). After spheroidization is once attained, it is necessary to heat the alloys to relatively high temperatures, depending on the chromium and silicon contents, before solution of the carbides is again affected; this is evident from the curves in Fig. 69, page 241.

It should be pointed out that typical structures developed in the groundmass of irons containing over 12 per cent chromium, air cooled in sections up to those of a 1.25-in. diameter transverse bar, differ from those developed in plain white iron. Depending on the amount of carbon held in solution, the groundmass may appear progressively as austenite, as discolored and decomposed austenite with precipitated carbides of submicroscopic size, as decomposed austenite containing carbides of visible size, or as ferrite containing carbides of varying size. Under normal rates of air cooling, these high-chromium cast irons do not show well defined pearlitic or martensitic structures but are usually sorbitic in appearance. As stated previously, a high silicon content with a given rate of cooling produces a more complete separation of carbides in the groundmass. A similar effect occurs on increasing chromium to or beyond the limit of the gamma phase.

129. Effect of Annealing on the Structure of High-chromium Cast Irons.—In line with the foregoing, annealing treatments on high-chromium cast irons can alter only the groundmass, and consequently the degree to which the irons may be softened depends on the relative percentages of the structure occupied by the groundmass as compared with the unaltered primary carbides. Obviously the lower carbon alloys with their lower proportion of primary carbides are subject to greater softening by annealing. As noted, the irons become more ferritic in character and progressively less affected by annealing treatments as the chromium is increased above a certain point. The amount of chromium necessary to reach this point rises with carbon content and falls with increased silicon content. It is clear from Valenta's work(166) that with low silicon contents (approximately 0.25 to 0.75 per cent) the high-chromium cast irons with 15 to 35 per cent chromium and 1.5 to 3 per cent carbon are subject to considerable hardening by air cooling from 1000°C. (1830°F.) and even by cooling in sand, particularly with a chromium-carbon ratio of 10 to 1. The Brinell hardness of the cast alloys (approximately 400) can be lowered to 275 to 350 by annealing 4 hr. at 1000°C. and slow cooling. A number of these low-silicon alloys in the higher carbon range tend to develop cracks on reheating after hardening. However, with the higher silicon irons containing approximately 2 3 to 2.5 per cent silicon, Valenta found air hardening to be suppressed. As a consequence, in the case of higher silicon irons the hardness values of irons as cast are not, in general, very different from those of annealed irons. Although this rule appears well established, it should be noted in considering absolute values that Valenta's results show numerous exceptions, which indicate that his fixed annealing temperature of 1000°C. (1830°F.) is probably not suitable for all the alloys considered. It is apparent, however, that in the higher carbon alloys containing over 2 per cent carbon and 2 per cent silicon some advantage in production of low hardness in the cast as well as in the annealed specimens is obtained by keeping the alloys in the ranges of 15 to 20 or 30 to 35 per cent chromium. In the lower chromium range the Brinell hardness after annealing varies from 310 to 350 depending on carbon content, as compared to values of 340 to 418 for as-cast specimens. At 25 per cent chromium comparable Brinell values are 315 to 450 and 340 to 450. This is in line with a few scattered results of unpublished machining experiments, which indicate more ready machinability for alloys containing 2.5 to 3 per cent carbon, 2 to 2.5 per cent silicon, and 15 to 20 per cent chromium than for similar alloys containing approximately 25 per cent chromium.

130. Annealing High-chromium Cast Irons Containing over 3.5 Per Cent Carbon.—Unpublished experiments on 15 per cent chromium irons containing 3.5 to 4.0 per cent carbon and 1.87 to 2.75 per cent silicon indicate that transverse or tensile properties are little affected by annealing treatments at 600 to 800°C. (1110 to 1470°F.), the specimens being held 3 hr. at temperature and furnace cooled. Higher temperature anneals, although of possible value in relieving strains and preventing cracking on later exposure of the alloys to heat, are not effective in improving significantly the transverse properties of the alloys, and with this high carbon content the alloys do not become machinable. In any annealing treatment the irons should be brought slowly and evenly to the annealing temperature and should be slowly cooled in order to prevent cracking.

131. Annealing High-chromium Cast Irons with Carbon under 3 Per Cent.—In high-chromium cast irons containing 1 to 3 per cent carbon and 1 to 3 per cent silicon appreciable softening can be obtained by annealing. For example, the hardness of such a series of cast alloys containing 17.5 per cent chromium was lowered from 85 to 135 Brinell units by holding 3 hr. at 800°C. (1470°F.) and furnace cooling. For a given alloy the temperature of maximum softening generally coincides with a temperature just below the transformation temperature as shown in Fig. 69. For this particular 17.5 per cent chromium series the alloys containing 1 per cent or less silicon showed maximum softening at 750°C. (1380°F.), those with 2 per cent silicon at 800 to 850°C. (1470 to 1560°F.), and those with 3 per cent silicon at 900 to 950°C. (1650 to 1740°F.). In accordance with Fig. 69, the annealing temperature for maximum softening also increases with chromium content. For example, a cast iron containing 1.98 per cent carbon, 24.93 per cent chromium, and 1.85 per cent silicon showed maximum softening from 418 to 302 Brinell on annealing at approximately 1050°C. (1920°F.), although a 950°C. (1740°F.) anneal was sufficient to drop the hardness to 340. If the chromium content exceeds that at which gamma phase can exist, the hardness of the alloy is not appreciably affected by annealing. Thus the hardness of 350 to 364 Brinell of an as-cast alloy containing 2.76 per cent carbon, 32.11 per cent chromium, and 1.74 per cent silicon was not affected by annealing, oil quenching, or water quenching from temperatures up to 1100°C. (2010°F.).

As would be expected, it is possible to reharden chromium cast irons, if the silicon and chromium contents are not high enough to prevent the appearance of gamma phase, by heating them to temperatures above that of transformation, followed by rapid cooling. For example, when the chromium content of the aforementioned alloy containing 2.76 per cent carbon was lowered to 24 or 19 per cent, quenching from 1100°C. (2010°F.) resulted in a hardness of approximately 650 Brinell.

To summarize, high-chromium cast irons containing over 3 per cent carbon normally cannot be softened to a machinable condition by annealing treatments, and their mechanical properties are only slightly affected. The principal advantage to be gained from an anneal is increased resistance of the irons to thermal shock, but the anneal should be performed carefully and at about 1000°C. (1830°F.) as a maximum.

On the other hand, high-chromium alloys containing 1 to 3 per cent carbon can be softened appreciably by annealing. Exceptions to this rule, of course, are irons containing sufficient chromium or silicon to place them outside the gamma-phase region, in which case the hardness of the alloys as cast is not materially affected by heat treatment. The annealing temperature for maximum softening corresponds to a temperature just below that of transformation of the particular iron. The position of the transformation varies, as shown in Fig. 69, with the carbon, silicon, and chromium contents. The irons can be rehardened by holding above the transformation temperature, followed by rapid cooling.

As noted previously, high-chromium cast irons containing up to 2.5 per cent carbon and 1.5 to 3.0 per cent silicon are normally sufficiently soft as cast for machining, but machinability can often be increased considerably by an anneal of the type described. Little information is available on the effect of annealing on mechanical properties, but improvement in ductility usually results and in some irons an increase of as much as 50 per cent in tensile strength has been obtained through annealing. Cast irons containing 2.5 per cent or less carbon exhibit the greatest resistance to thermal shock, and from the existing data, 3.0 per cent carbon is apparently the maximum that should be employed in installations subject to relatively sudden thermal changes.

In the heat treatment of chromium cast irons containing more than 1 per cent carbon, it has been observed that the irons resist grain growth to a remarkable degree even when exposed for relatively long periods at temperatures up to 1100°C. (2010°F.).

C. SPECIAL PROPERTIES

The important properties of high-chromium cast irons from an industrial standpoint are the following: (*a*) Resistance to oxidation and to structural decomposition at high temperatures; (*b*) resistance to wear and ability to be work hardened; (*c*) resistance to corrosion; and (*d*) high fluidity.

132. Resistance to Oxidation and Structural Decomposition at High Temperatures.—The high-chromium cast irons, like the lower carbon chromium irons, show great resistance to oxidation. Strangely enough, high carbon content has been found to have only a minor effect on the heat resistance or scaling of high-chromium cast irons. Thyssen(512) determined the gain in weight after 150 hr. at 950°C. (1740°F.) of specimens of high-chromium cast irons containing approximately 15 to 40 per cent chromium. The silicon content of these irons was approximately 1 per cent and the carbon varied from 1 to 3 per cent. If the gain in weight of the specimens due to oxidation is plotted against carbon content, it is at once evident that the higher carbon irons do not oxidize more readily than the lower carbon irons, and, in fact, there is a trend toward less oxidation as the upper end of the carbon range is approached. The approximate effect of carbon on the oxidation loss of higher silicon 15 and 25 per cent chromium cast irons after 48 hr. at 1000°C. (1830°F.) has been investigated by Burgess.* Plain gray irons containing 2.5 to 3.5 per cent carbon and 2 per cent silicon, run as a check in the tests, showed an average loss of 24.20 per cent, whereas irons containing approximately 25 per cent chromium and 1.77 to 2.28 per cent silicon showed oxidation losses or weight gains of only 0.10 per cent or less, although carbon varied from 1.22 to 4.04 per cent in these latter specimens. In the 15 per cent chromium irons, high carbon appeared to have more effect on the scaling resistance. The scaling loss at 1000°C. (1830°F.) in this last series, however, remained less than 0.40 per cent with up to 2.50 per cent carbon. These irons contained 2.59 to 2.92 per cent silicon.

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* C. O. Burgess, unpublished investigation.

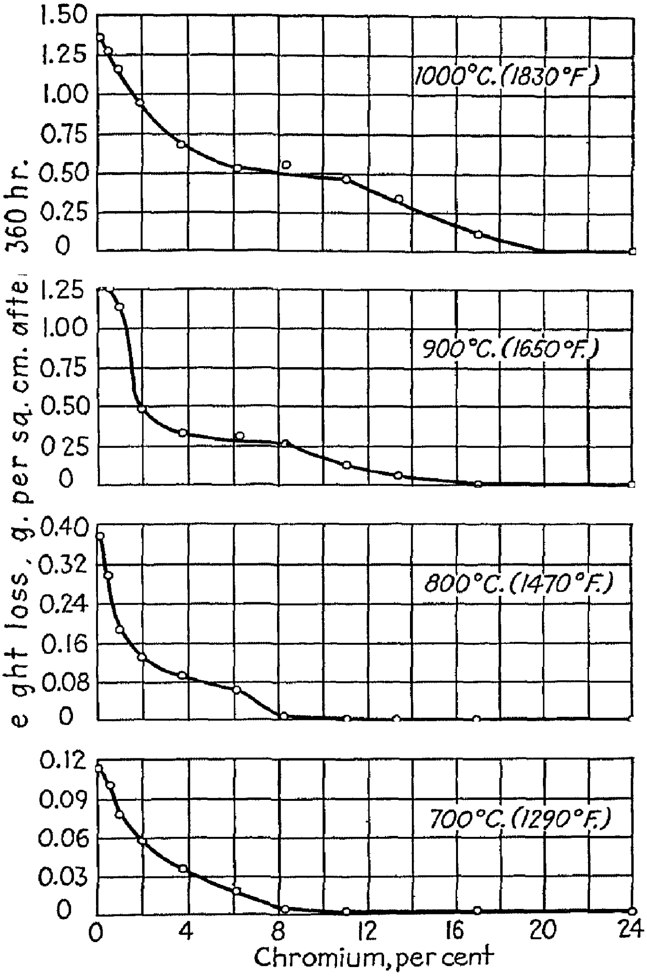

FIG. 72.—Effect of chromium on the oxidation of cast iron containing approximately 3 per cent carbon and 2.25 per cent silicon, at 700 to 1000°C. (1290 to 1830°F.). (*Burgess.*)

The considerable effect of chromium on oxidation resistance of cast iron is clearly evident in the tests of Thyssen(512) and others. The degree to which chromium content decreases oxidation loss at four different temperature levels, 700, 800, 900, and 1000°C. (1290, 1470, 1650, and 1830°F.), has also been investigated by

Burgess.* A constant base iron was employed in these tests, containing approximately 3 per cent carbon and 2.25 per cent silicon. The weight loss by oxidation at the various temperature levels is shown in the curves of Fig. 72. Oxidation resistance is apparently a direct function of the chromium content, reaching a maximum at the highest percentage of chromium employed, *viz.*, 25 per cent. Houdremont and Wasmuht(182) reported that high-chromium cast irons containing 34 per cent chromium and 1.1 per cent to 3.1 per cent carbon are immune to oxidation at 1100°C. (2010°F.). No evidence of growth at elevated temperatures has been noted in any cast iron containing over approximately 12 per cent chromium.

Silicon decreases the oxidation of high-chromium cast iron, and tests indicate that it plays an important part in the oxidation resistance of 15 per cent chromium cast irons at 1000°C. (1830°F.). In these tests the oxidation loss dropped from approximately 6 to 0.14 per cent as the silicon increased from 1.29 to 2.59 per cent. In chromium cast irons containing 12 per cent or more chromium it would appear that the addition of 1 per cent silicon confers an oxidation resistance equivalent to approximately 2 per cent increase in chromium. However, as noted in the discussion of the heat treatment of high-chromium cast irons, the permissible addition of silicon is limited if sensitivity to thermal shock or cracking is to be avoided, and silicon apparently should not materially exceed 2 per cent in irons containing 2 per cent or more carbon.

In general, the silicon-bearing 15 to 18 per cent chromium cast irons appear suitable for use at working temperatures up to 940°C. (1725°F.). For example, a specimen of a malleableizing box of this type of iron showed only the formation of a thin, tightly adherent scale after 57 anneals at a top temperature of 940°C. (1725°F.) and no evidence of progressive oxidation. At higher temperatures, *e.g.*, up to 1100°C. (2010°F.), cast irons containing 24 to 35 per cent chromium appear to be most suitable.

As stated previously, the chromium carbides in high-chromium cast irons are relatively immune to decomposition or alteration and, therefore, aid the iron in retaining rigidity and strength at elevated temperatures. MacQuigg(40) stated that in high-temperature tensile tests on chromium iron it was found that an increase in carbon definitely shifted the knee of the temperature versus tensile strength curve toward higher temperatures. Houdremont and Wasmuht(182) found an actual increase in high-temperature strength up to 500°C. (930°F.) in a cast iron containing 2.3 per cent carbon, 1.4 per cent silicon, and 34.2 per cent chromium. The use of sufficient carbon to yield a fairly fine-grained cast iron also appears to delay or prevent grain growth in the cast irons on extended exposures to temperatures of 1000°C. (1830°F.). This is probably connected with actual mechanical limitation of grain growth due to the presence of insoluble carbides in the iron matrix.

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* See footnote, p. 250.

The amount of carbon that can be employed advantageously in the high-chromium cast irons is governed by considerations previously outlined. For example, with a given chromium content the degree of resistance of the irons to thermal shock progressively decreases with increasing carbon. Although successful installations containing over 3 per cent carbon have been reported, a carbon content of 3 per cent is probably the maximum normally advisable. A further increase in both strength and resistance to heat cracking is evident in the irons containing a maximum of 2.5 per cent carbon; and at present these lower carbon cast irons find the widest application.

133. Resistance to Wear and Ability to Work Harden.—The high-chromium cast irons possess considerable resistance to wear and can be work hardened. MacQuigg(40) found that in an industrial installation a chromium iron containing 2.72 per cent carbon and 26.41 per cent chromium excelled plain chilled cast iron and equaled manganese steel in wear resistance. It is this quality of high-chromium cast irons that makes advisable a relatively heavy cut in machining. It has been found, for example, that a high-chromium cast iron containing approximately 3 per cent carbon, 15 per cent chromium, and 2.35 per cent silicon was machinable when a moderately heavy cut was used, but if a very fine cut was employed the surface of the iron was sufficiently hardened to preclude machining with ordinary cutting tools. No doubt, the wear resistance of the high-chromium cast irons is merely an extension of the well-known wear-resisting property of steels containing 2 per cent carbon and 12 per cent chromium. Probably one of the most valuable properties of the high-chromium cast irons is that their structural character develops considerable wear resistance at elevated temperatures.

134. Resistance to Corrosion.—The high-chromium cast irons appear to be distinctly inferior to low-carbon irons of similar chromium content as regards stainlessness upon exposure to the atmosphere or acid media. This has been ascribed to the fact that in the formation of chromium carbide the groundmass of the alloy is depleted in chromium, approximately 10 per cent chromium being combined with each 1 per cent carbon. However, the high-carbon irons have been reported to be fairly resistant to sea water, mine waters, and weak acids, the degree of resistance varying with their composition.(473) There is evidence to lead to the belief that, after initial staining or scaling, progressive corrosion is considerably decreased, probably partly owing to the presence of chromium carbides. Tull(300) reported that high-chromium cast irons containing approximately 2.5 per cent carbon, 2.5 per cent silicon, and 11 or 14 per cent chromium, when exposed to an atmosphere of carbon dioxide, sulphur dioxide, air, and steam at 500°C. (930°F.), showed an initial light scale after 288 hr., but no further increase in scaling after an additional 240-hr. exposure. Phillips(332) stated that high-chromium cast

TABLE 75.—RESISTANCE TO NITRIC ACID OF CAST IRON CONTAINING (*A*) 1.1 PER CENT CARBON, 1.3 PER CENT SILICON, AND 33.6 PER CENT CHROMIUM, AND (*B*) 2.3 PER CENT CARBON, 1.4 PER CENT SILICON, AND 34.2 PER CENT CHROMIUM*

Acid concentration, per cent	Specific gravity of acid	Temperature of test		Weight loss, g. per sq. m. per hr.	
		°C.	°F.	Alloy *A*	Alloy *B*
7	1.04	20	70	<0.1	<0.1
		Boiling		<0.1	<0.1
37	1.23	20	70	<0.1	<0.1
		Boiling		0.1 to 1.0	0.1 to 1.0
66	1.40	20	70	<0.1	<0.1
		Boiling		0.1 to 1.0	0.1 to 1.0
Fuming	1.52	20	70	0.1 to 1.0	0.1 to 1.0
		40	105	>10	>10

* Houdremont and Wasmuht.(182)

irons give excellent service in contact with salt solution and molten lead and aluminum.

Table 76.—Corrosion Resistance in Various Media of Cast Iron Containing (*A*) 1.1 Per Cent Carbon, 1.3 Per Cent Silicon, and 33.6 Per Cent Chromium, and (*B*) 2.3 Per Cent Carbon, 1.4 Per Cent Silicon, and 34.2 Per Cent Chromium*

Corroding medium	Temperature of test		Weight loss, g. per sq. m. per hr.	
	°C.	°F.	Alloy *A*	Alloy *B*
30 per cent H_2SO_4 + 5 per cent HNO_3 + 65 per cent water...	50	120	<0.1	<0.1
Saturated aqueous solution of sulphurous acid....	20	70	<0.1	<0.1
10 per cent phosphoric acid, specific gravity 1.05....	Boiling		<0.1	<0.1
45 per cent phosphoric acid, specific gravity 1.30....	Boiling		<0.1	<0.1
80 per cent phosphoric acid, specific gravity 1.64....	Boiling		3.0 to 10.0	3.0 to 10.0
10 per cent acetic acid, specific gravity 1.01....	Boiling		<0.1	<0.1
80 per cent acetic acid, specific gravity 1.07....	Boiling		<0.1	<0.1
100 per cent acetic acid, specific gravity 1.05....	Boiling		<0.1	<0.1
Aqueous solution of sodium hydroxide, specific gravity 1.16....	50	120	<0.1	<0.1
Aqueous solution of sodium hydroxide, specific gravity 1.16....	Boiling		<0.1	<0.1
50 per cent solution of sodium hydroxide, specific gravity 1.53....	Boiling		>10.0	>10.0
Ammonium nitrate, 50 per cent solution....	Boiling		<0.1	<0.1
Ammonium sulphate, 50 per cent solution....	Boiling		<0.1	<0.1
Saturated calcium hypochlorite	40	105	0.1 to 1.0	0.1 to 1.0
30 per cent solution of ferric chloride	20	70	>10.0	>10.0

* Houdremont and Wasmuht.(182)

With sufficient chromium it is possible to render these cast irons stainless and resistant to more severe corrosive media.(182) The rule usually applied in such cases is to ensure a chromium content of approximately 10 to 12 per cent in addition to the chromium entering into combination as carbide.

Houdremont and Wasmuht,(182) in connection with the study of the structure and properties of cast alloys containing 34 per cent chromium and (*A*) 1.1 per cent carbon and 1.3 per cent silicon and (*B*) 2.3 per cent carbon and 1.4 per cent silicon, determined their relative resistance to nitric acid and a variety of other corrosive media. Some of their data are given in Tables 75 and 76. Tests were made without removal of the casting skin.

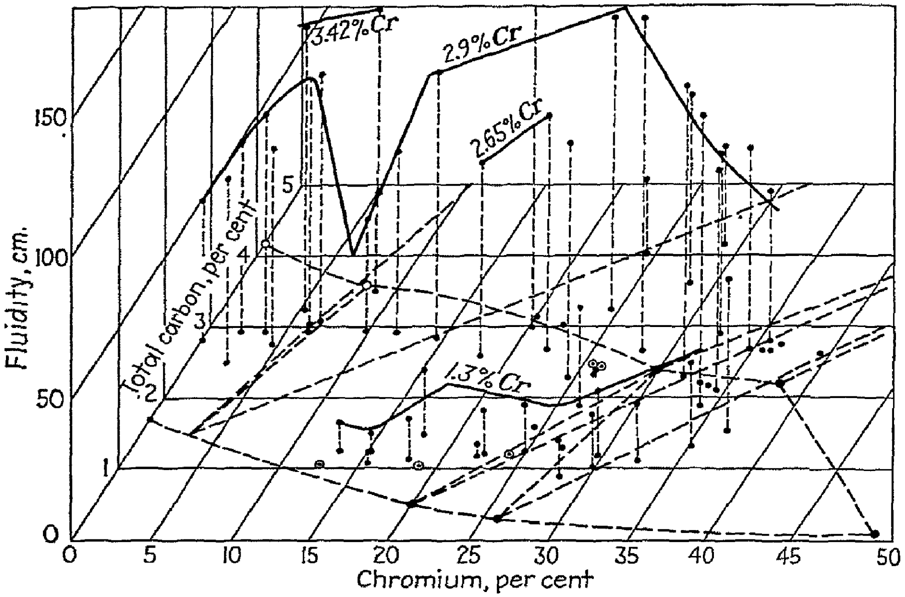

FIG. 73.—Effect of chromium on the fluidity of cast iron at 1400°C. (2550°F.). (*Thyssen.*(512))

An alloy containing 3.1 per cent carbon and 35 per cent chromium was also tested, but the casting skin was not so resistant to the atmosphere as that of alloys *A* and *B*. In the polished state, however, all three alloys were equally rust resistant.

The few data on the effect of chromium on the corrosion resistance of cast iron have been summarized recently.(515) The resistance of cast iron for 528 hr. to a synthetic smoke atmosphere of carbon dioxide, sulphur dioxide, steam, and air at 500°C. (930°F.) is given as follows:

Chromium, per cent	Weight loss, g. per sq. cm., in 528 hr.
0	0.0242
11	0 0080
14	0.0071

135. Fluidity.—As would be expected from their high carbon content, the high-chromium cast irons possess greater fluidity than lower carbon alloys. Thyssen(512) determined the flowing properties, using a "Berger" mold. His results are shown in Fig. 73, where, corrected to a pouring temperature of 1400°C. (2550°F.), the fluidity, in centimeters, is plotted against composition. In general "the results confirm the rule established by Portevin that the most fluid cast irons are in the neighborhood of the eutectic line and the fluidity diminishes as the castings depart from this line into either the hypoeutectic or hypereutectic fields." The relatively high fluidity of the high-chromium cast irons, which permits casting intricate shapes, is of importance from the viewpoint of the foundryman.

D. COMPOSITION AND APPLICATION

136. Types of Industrial High-chromium Cast Irons.—The greatest amount of commercial development to date, particularly in the United States, has been confined to the low-carbon high-chromium irons, which, as a rule, differ from the chromium cast irons in containing lower quantities of carbon and silicon and at least 20 per cent chromium. The companies manufacturing these irons are known to produce occasionally alloys approximating the high-chromium cast irons in analysis,(269,332) but these do not appear to have been assigned distinctive trade names. On the other hand, in recent years the widespread manufacture of high-chromium cast irons has come into vogue in Europe. The products are definitely identified in descriptive literature as cast irons and are given various trade names. For example, Valenta(166) reported "Ferchromit" and "Neochrom" of the chromium cast-iron type, presumably made in a wide variety of analyses. Such irons may contain up to 1.5 per cent carbon and up to 2.5 per cent silicon, and usually contain 25 per cent chromium. Guronite is another example and is made in two grades, Grade I containing 0.7 to 2.6 per cent carbon and 15 to 27 per cent chromium, and Grade II containing 0.7 to 2.3 per cent carbon and 20 to 40 per cent chromium; the latter may contain also 2.5 to 3.5 per cent molybdenum. The silicon content is reported as between 10 and 20 per cent under the carbon content. Some other irons identified as high-chromium cast irons are listed in Table 77. The analyses in Table 77 are only approximate.

TABLE 77.—ANALYSIS OF SOME EUROPEAN COMMERCIAL HIGH-CHROMIUM CAST IRONS

Type of commercial iron or trade mark	Composition, per cent				Approximate Brinell hardness
	C	Cr	Si	Ni	
Good heat-resistant irons..	1.6	9.2			273
Highly heat-resistant irons	2.17	23.5		0.32	300
Wegucit	2.5	30.0	3.0		370
Alferon....	1.98	23.5			363
Nirostaguss...	1.1 to 3.1	34.0	1.2 to 1.5		250 to 350

Apparently they are subject to wide variations depending on the service to which the castings are to be exposed. For example, the chromium will be raised to 30 per cent or more if stainlessness and high resistance to corrosive agents are required in a particular installation. It is to be noted that, despite the high hardness in several cases, all these irons are reported to be machinable.

Gaps are evident in Table 77 particularly concerning cast irons containing 15 to 20 per cent chromium and approximately 1.0 to 2.5 per cent silicon. Recent unpublished work indicates that they are suitable in heat-resistant applications where very high corrosion resistance is not required.

137. Applications of High-chromium Cast Irons.—Some of the uses for which high-chromium cast irons have been found particularly adaptable are annealing boxes, furnace and burner parts, nozzles, tuyere castings, protecting tubes, stoker parts, conveyor parts, grates, and all cast parts required to possess resistance to scaling and to wear at elevated temperature and in contact with corrosive gases. Rolls of various types have been successfully made and applied where resistance to wear or high temperature, or maintenance of a highly polished surface, is of importance. It is reported that the field of ornamental castings made from the higher chromium cast irons is growing.

E. AUTHORS' SUMMARY

1. Cast irons containing 12 to 20 per cent chromium are produced in the cupola, air furnace, or electric furnace; those containing from 20 to 35 per cent chromium are generally produced in electric furnaces; and those with up to 15 per cent chromium and a carbon content under 3 per cent may be produced in a cupola; 1.50 to 2.75 per cent silicon is usual in such irons.

2. Metallographically, high-chromium cast irons differ from ordinary cast irons; chromium is a strong carbide former and one or more chromium carbides may appear, with or without iron carbide.

3. Upon addition of chromium to cast iron containing 2 to 3.5 per cent carbon and 1.5 to 3 per cent silicon, the hardness increases as 5 per cent chromium is approached, then remains nearly constant as 10 per cent chromium is approached. In this range, the metal is ordinarily unmachinable; however, upon further addition of chromium, hardness is decreased somewhat. These high-chromium cast irons are machinable if special technique is used.

4. The effect of carbon on the structure and properties of high-chromium cast iron is so complex that it cannot be summarized readily.

5. Ordinary additions of silicon result in no special structural constituent; they do, however, refine the carbide structure, increase resistance to corrosion, decrease air hardening, and decrease dimensional changes on heat treatment. Large additions of silicon increase the tendency to crack during water quenching and reduce machinability by hardening the ferritic matrix.

6. Information on the effect of additional elements is scarce. There is indication that aluminum is an effective suppressor of air hardening, but that castings become weak and brittle as this element approaches 3 per cent. Molybdenum in the neighborhood of 3 per cent increases resistance to corrosion. Titanium is said to reduce primary grain size. Additions of nitrogen, nickel, copper, vanadium, and zirconium have been made, but results are too few to permit definite statements.

7. High-chromium cast irons are relatively unresponsive to heat treatment, but this characteristic is one that renders them

useful for elevated-temperature service. Castings can be softened by annealing, especially if the carbon content is less than 3 per cent. The temperature of annealing for maximum softening is ordinarily just below that of transformation. The temperature for a given alloy, therefore, depends upon composition. Castings containing more than 3 per cent carbon usually cannot be softened to a machinable condition; they can, however, be annealed for the purpose of increasing resistance to thermal shock.

8. From a utilitarian point of view, the important properties of high-chromium cast irons are resistance to oxidation and corrosion, resistance to structural decomposition at high temperature, resistance to wear, work hardenability, and fluidity.

CHAPTER IX

CONSTITUTION OF COMPLEX IRON-CHROMIUM ALLOYS

The Iron-chromium-nickel System—Other Systems—Authors' Summary

Interest in the so-called "austenitic" stainless steels, of which the low-carbon grade containing nominally 18 per cent chromium and 8 per cent nickel is a familiar example, is sufficient to justify extensive investigation of their constitution. The result is that the iron-chromium-nickel diagram is established qualitatively in its entirety and at least semiquantitatively in part; this is sufficient to permit rational interpretation of the behavior of the alloys under a variety of treatments and conditions.

Investigation of the iron-chromium-nickel diagram is hampered by the fact that reaction rates are very low over important ranges of composition and temperature; however, diagrams for non-equilibrium conditions are useful in that they are better able than diagrams for equilibrium conditions to interpret the behavior of alloys heated and cooled at rates comparable with those of ordinary mill practice.

Iron-chromium-manganese alloys have been considered as a possible substitute for comparable alloys containing nickel, as well as in their own right. Their constitution also has been the subject of considerable investigation, but results are not so complete as those on the iron-chromium-nickel system.

For completeness, brief notes on the iron-chromium-silicon, iron-chromium-phosphorus, and iron-chromium-sulphur systems are given in this chapter.

A. THE IRON-CHROMIUM-NICKEL SYSTEM

The iron-chromium-nickel diagram is useful from a practical point of view because it permits simple interpretation of otherwise mysterious behavior of the alloys. From a theoretical point of view, the diagram is interesting in that it contains an unusual construction owing to the appearance of an intermediate phase in the solid state.

138. Early Investigations of the Constitution of Iron-chromium-nickel Alloys.—The first investigation of the structure of iron-chromium-nickel alloys, containing from 0.1 to about 0.5 per cent carbon, was conducted in the years 1909 to 1912 by Strauss,(56) who summarized his data in the form of a structural diagram confined to the iron-rich corner. It was observed that forged alloys containing 20 per cent chromium and 7 per cent nickel contained free carbide, and that the carbide could be dissolved and retained in solution by heating to 1150 to 1250°C. (2100 to 2280°F.), followed by rapid cooling. The structure after such treatment was austenitic (gamma phase). Reheating to 700°C. (1290°F.) caused reprecipitation of carbide, especially in the grain boundaries.

The first comprehensive investigation of the constitution of iron-chromium-nickel alloys, by Bain and Griffiths,(80) was described in 1927. Some 70 samples of fairly high purity, containing up to about 55 per cent chromium and 30 per cent nickel, were prepared. Specimens were annealed, reheated to various temperatures ranging from 900 to 1300°C. (1650 to 2370°F.), then quenched in water. The phases present were determined mostly by means of the microscope, although X-ray analysis was used in certain instances. One of the most important findings was the discovery of a hard, brittle, intermediate phase that appeared upon annealing for a sufficient length of time at temperatures "probably below 950°C. (1740°F.)." It was also found that the upper temperature limit of the phase was greater in alloys containing 10 per cent nickel than in nickel-free alloys. (Later and detailed information on the phase, now generally called "sigma," is given in the first volume of this monograph.) Other results indicated a greater range of stability of the alpha (ferrite) phase than had been shown by Strauss. This was due to the fact that Bain and Griffiths worked with lower carbon steels. Data obtained by Hatfield(86) led him to conclude that steels containing 18 per cent chromium and 8 per cent nickel consist wholly of the gamma phase at heat-treating temperatures, and that this phase persists at ordinary temperature.

139. Later Data.—In 1930, Krivobok and Grossmann(149) summarized in graphical form a vast amount of metallographic work on steels containing 0.05 to 0.6 per cent carbon, 18 per cent chromium, and 2, 4, 8, and 12 per cent nickel. Heating temperatures extended to the range of incipient fusion, consequently some information was obtained on regions in which the liquid phase participated. Sections for the aforementioned chromium and nickel contents and variable carbon content showed clearly that nickel increases the area of the gamma-phase field. A paper by Aborn and Bain,(132) published the same year, included the most exhaustive attempt at that time to arrive at a complete ternary diagram. That these investigators were fully aware of the experimental difficulty attached to such effort is evident from the following statement:

> The outstanding property of the alloys containing substantial proportions of chromium and nickel is their sluggishness toward all action involving diffusion and change of phase at all moderate temperatures. For example, the "18-8" alloy itself is truly stable only as ferrite at temperatures below about 400°C. (750°F.) . . . but indefinite maintenance at this temperature will not in itself cause the alloy, as quenched in the austenitic condition, to transform from metastable austenite to stable ferrite. Cold work, however, supplies the necessary atomic "stirring" to induce the alloy, at least partially, to assume its stable condition. The word "stable" is here used in its physical-chemical sense, and not, as occasionally found, in the sense of "persistent."

A more satisfactory description of the diagram was given several years later by the same authors.(517)

140. Contiguous Binary Diagrams.—The iron-chromium and iron-nickel diagrams are discussed in detail in previous monographs of this series, consequently they need not be reviewed here. The first work on the chromium-nickel diagram was reported in 1908 by Voss,(4) whose data showed that solutions of each element in the other melt at lower temperatures than the pure components. More recent investigations, by Nishigari and Hamasumi,(119) Tasaki,(131) Wever and Jellinghaus,(209) Matsunaga,(285) and Jette, Nordstrom, Queneau, and Foote,(324) were reviewed by Hansen.(424) Hansen's diagram indicates that a eutectic is formed at roughly 50 per cent nickel at 1340°C. (2445°F.). The results of the latest investigation, that by Jenkins, Bucknall, Austin, and Mellor,(457) are shown in Fig. 74.

These data were chosen for the construction of a provisional iron-chromium-nickel diagram.

141. The High-temperature Portion of the Iron-chromium-nickel Diagram.—The most extensive data on the high-temperature portion of the iron-chromium-nickel diagram were supplied by Wever and Jellinghaus(209) and by Jenkins, Bucknall, Austin, and Mellor.(457) The former examined approximately 200 alloys, including 7 iron-nickel, 18 iron-chromium, and 21 chromium-nickel alloys. Most of the ternary alloys contained more than 75 per cent iron; they were prepared from electrolytic iron, shot nickel, and 98 per cent chromium by melting under hydrogen in a high-frequency furnace. There was considerable variation of silicon content; *viz.*, from 0.1 to 1 per cent. The alloys of Jenkins and coworkers were somewhat purer, the principal impurities being up to 0.75 per cent insoluble matter (mostly Cr_2O_3) and less than 0.16 per cent silicon. Five series, containing approximately 10, 20, 30, 40, and 50 per cent chromium, were prepared by melting under hydrogen in a high-frequency furnace.

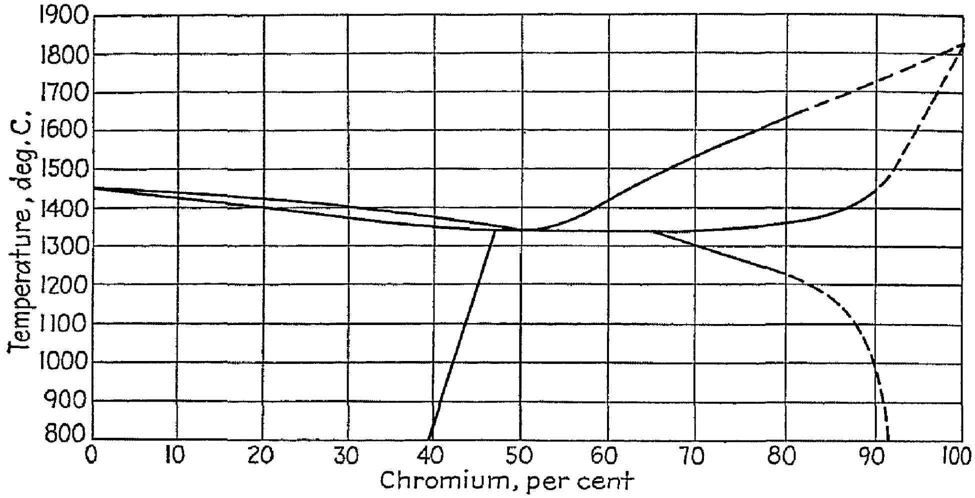

FIG. 74.—The chromium-nickel diagram. (*Jenkins, Bucknall, Austin, and Mellor.*(457))

Both Wever and Jellinghaus and Jenkins and his associates reported thermal analyses as projected isotherms as well as in tables. For comparison of these data, several constant-chromium vertical sections were constructed; these indicated that the

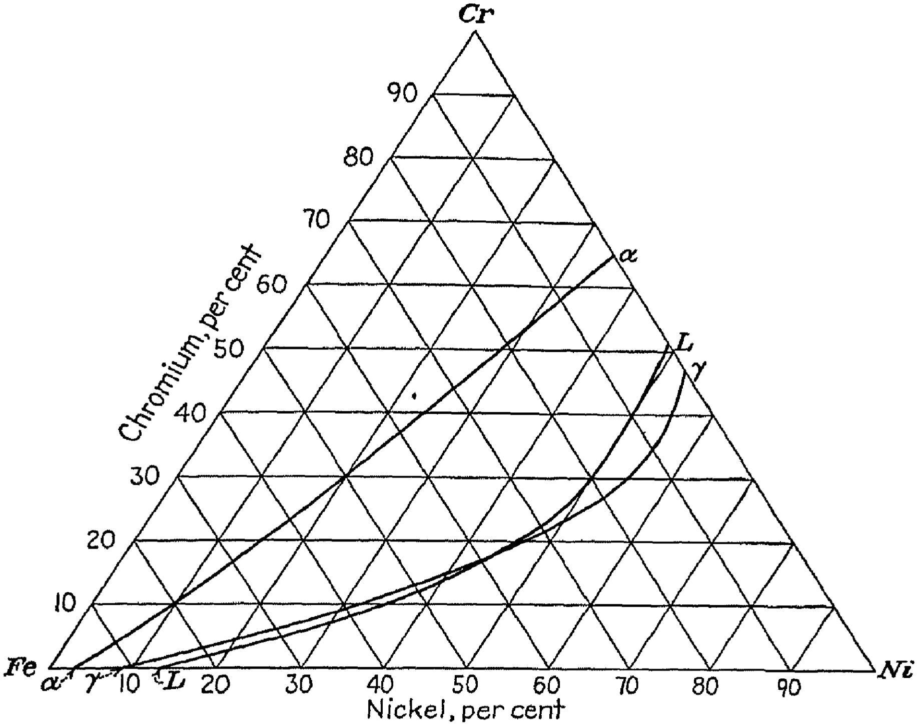

FIG. 75.—Basal projection of lines of twofold saturation.

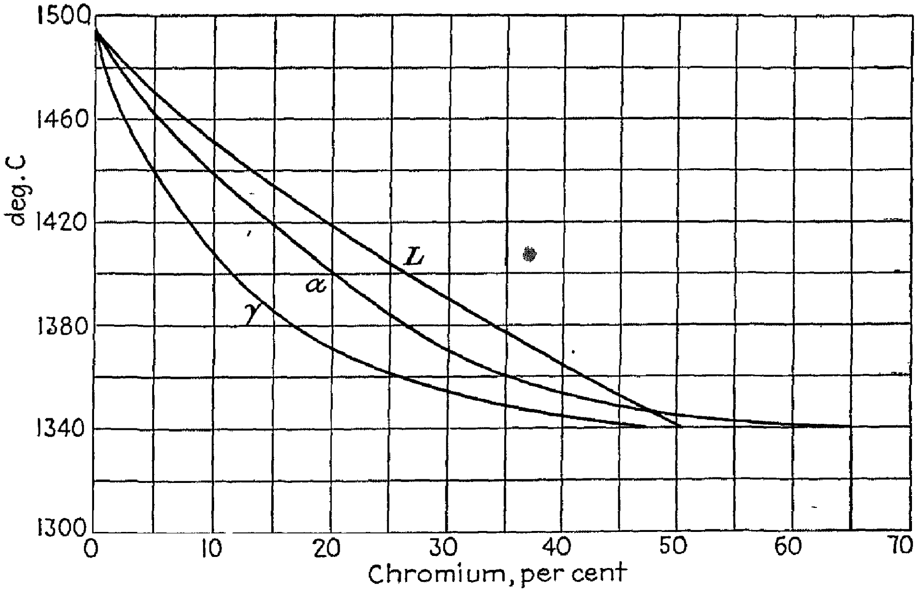

FIG. 76.—Temperature variation of alpha, gamma, and liquid.

transition from peritectic- to eutectic-type transformation takes place in the neighborhood of 20 per cent chromium. A basal projection of the lines of twofold saturation is shown in Fig. 75; the temperature variation of these lines is estimated in Fig. 76. From these projections and the vertical sections, isothermic sections at 1500, 1400, and 1350°C. (2730, 2550, and 2460°F.), shown in Figs. 77 to 79, were constructed. The section at 1500°C. shows no three-phase equilibrium; that for 1400°C. shows the three-phase arrangement that is characteristic of peritectic equilibrium; and that for 1350°C. is characteristic of eutectic equilibrium. Vertical sections are shown later.

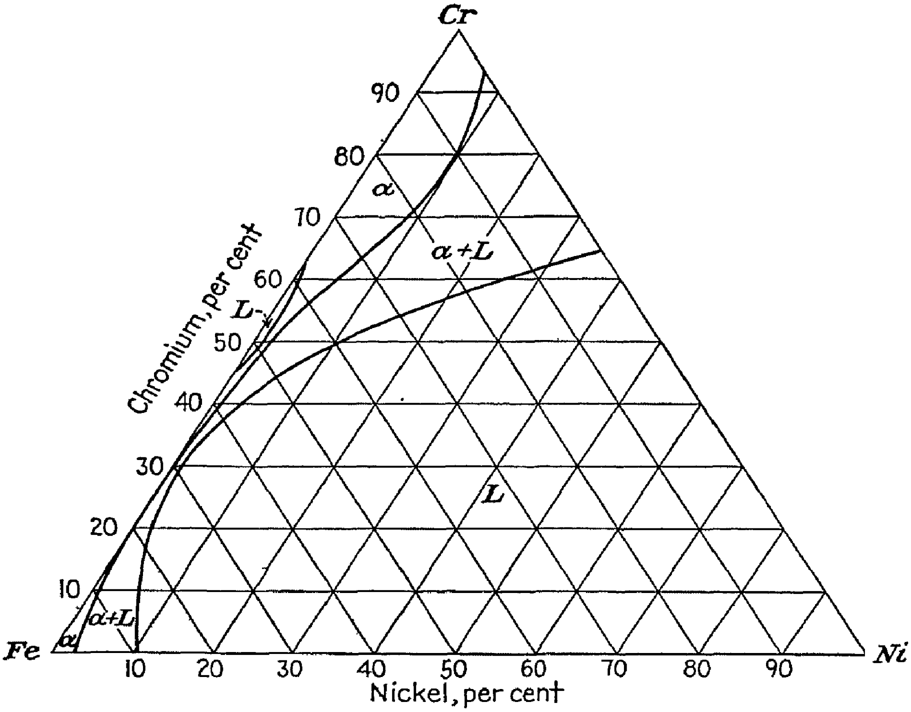

FIG. 77.- Isothermic section at 1500°C. (2730°F.).

142. The Low-temperature Portion.—Reliable data on solubilities in solid iron-chromium-nickel alloys are few. Figure 80 is an isothermic section at 1200°C. (2190°F.) constructed from data of Schafmeister and Ergang.(507) Alloy compositions studied were such that the gamma-phase boundary could be placed with some certainty, but this is not true of the alpha-phase boundary. Sections at lower temperatures are shown later rather than here, because of a complication introduced by a new solid phase.

At this point it may be illuminating to introduce Fig. 81, a series of semiquantitative constant-chromium sections given by Bain and Aborn.(517) Because of the low reaction rates of iron alloys containing chromium or nickel, or both, at temperatures even as high as 600°C. (1110°F.), it is nearly impossible to attain equilibrium. Furthermore, these materials are ordinarily used as quenched from a relatively high temperature, consequently there is little need for quantitative accuracy at the lower temperatures. The sections given are adequate to show the general effects of composition on the positions of the phase boundaries. Under certain conditions of composition and heat treatment, the embrittling intermediate phase appears; it also must be shown in any iron-chromium-nickel diagram that claims even qualitative completeness for equilibrium conditions.

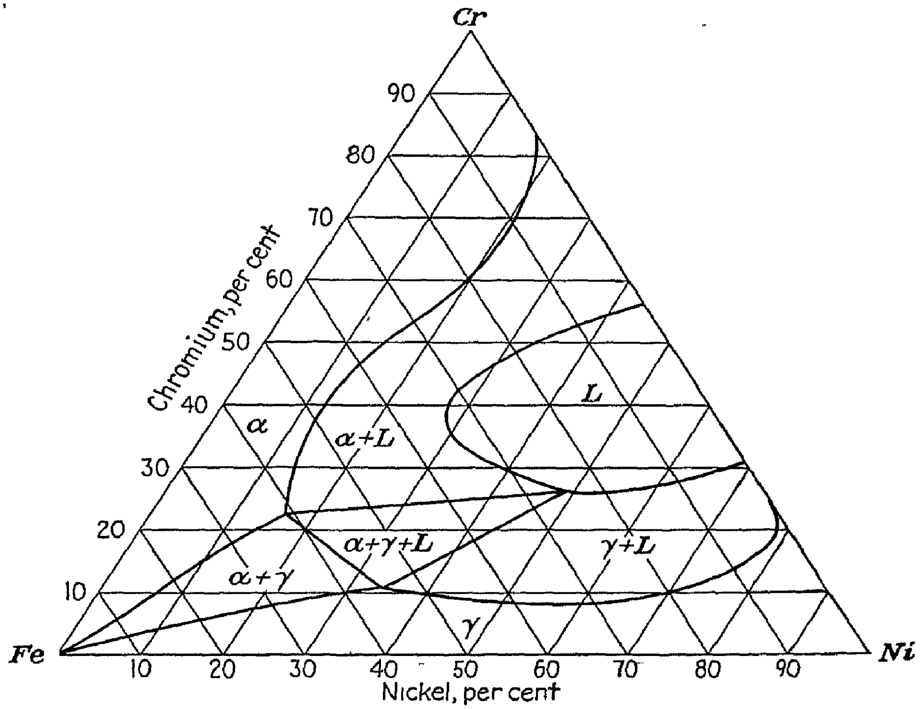

FIG. 78.—Isothermic section at 1400°C. (2550°F.).

143. The Sigma-phase Region.—The intermediate phase called "sigma" of the iron-chromium system, described in detail in Volume I, appears over a substantial concentration range in iron-chromium-nickel alloys. Its effect on the diagram was shown qualitatively by Marsh(525) and semiquantitatively by Schafmeister and Ergang.(507) The latter prepared alloys containing 0.1 per cent carbon or less, about 0.3 per cent silicon, and 0.3 to 0.5 per cent manganese. Specimens were annealed 2 hr. at 1200°C. (2190°F.), 200 and 1000 hr. at 650 and 800°C. (1200 and 1470°F.), and water quenched. The phases were identified by microscopic, X-ray, magnetic, and hardness tests. Results, in replotted form, are given in Figs. 82 and 83. Comparison of the sections for 650 and 800°C. shows relatively small differences. Since it is unlikely that the 650°C. section would undergo much change at lower temperatures, it may be assumed that this section is valid for room temperature. The boundaries may be susceptible to impurities; it is known that silicon increases the concentration range of the sigma phase, but results of Schafmeister and Ergang indicate that carbon in amounts up to at least 0.3 per cent is without appreciable influence.

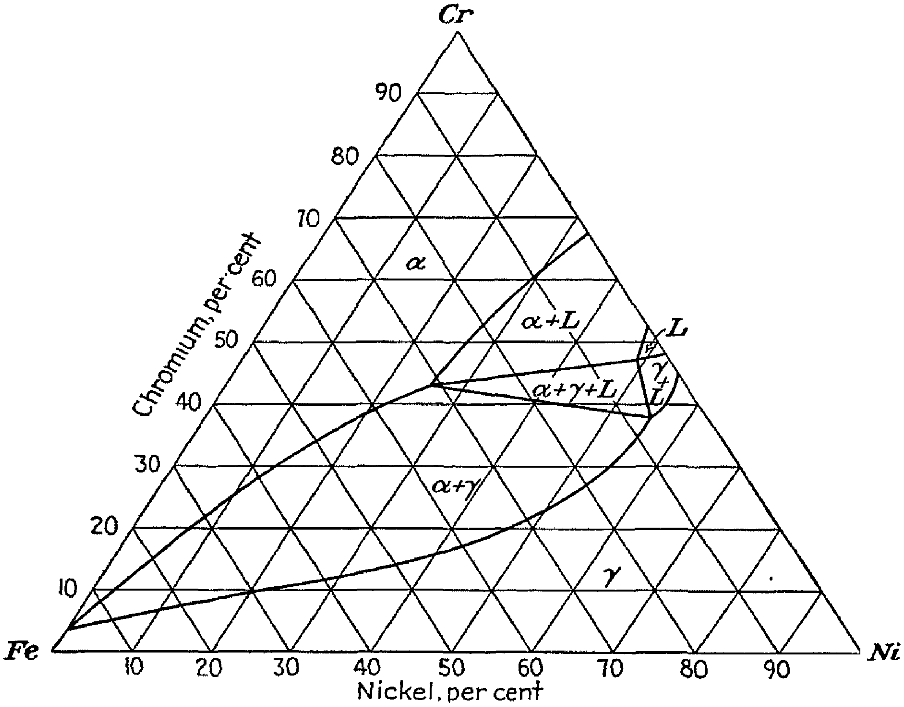

FIG. 79.—Isothermic section at 1350°C. (2460°F.).

Close inspection of the data and diagrams of Schafmeister and Ergang leads to the conclusion that further work is likely to cause some adjustment of the various boundaries, but there is little doubt that the qualitative details of the sigma-phase region are correct. In one small detail the diagram constructed by Marsh seems more probable; *viz.*, a few scattered experimental observations indicate that nickel increases the temperature range of stability of the sigma phase rather than decreases it, as shown by Schafmeister and Ergang.

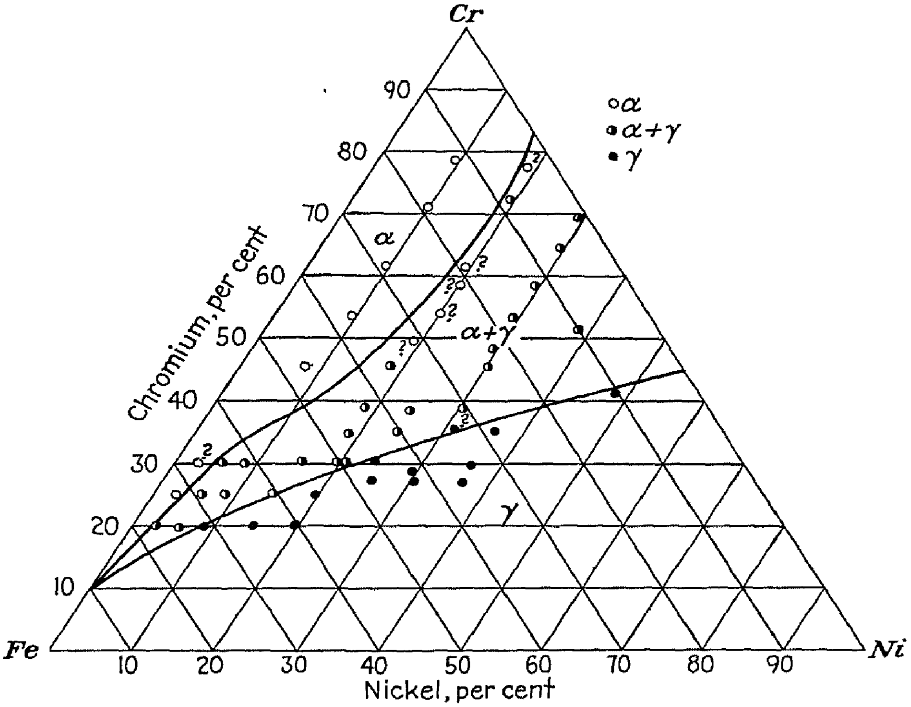

FIG. 80.—Isothermic section at 1200°C. (2190°F.). (*Based on data of Schafmeister and Ergang.*[507])

144. Working Sections of the Diagram.—Because of the industrial importance of alloys of the 18-8 type, their constitution is discussed in some detail. A section of the ternary diagram at 18 per cent chromium is shown in Fig. 84. By way of review it may be useful to follow the processes in a substantially carbon-free 18-8 alloy upon cooling from the melt, assuming that sufficient time is allowed to complete all transformations. No change takes place until the liquidus surface is passed, after which alpha phase (ferrite) separates. The composition of the participating phases at any temperature within the alpha-plus-liquid range cannot, in general, be determined from such a section, because the tie lines do not, in general, lie in the plane of the section. Upon reaching the solidus surface, however, the liquid phase disappears and alpha phase remains, of composition given by the intersection

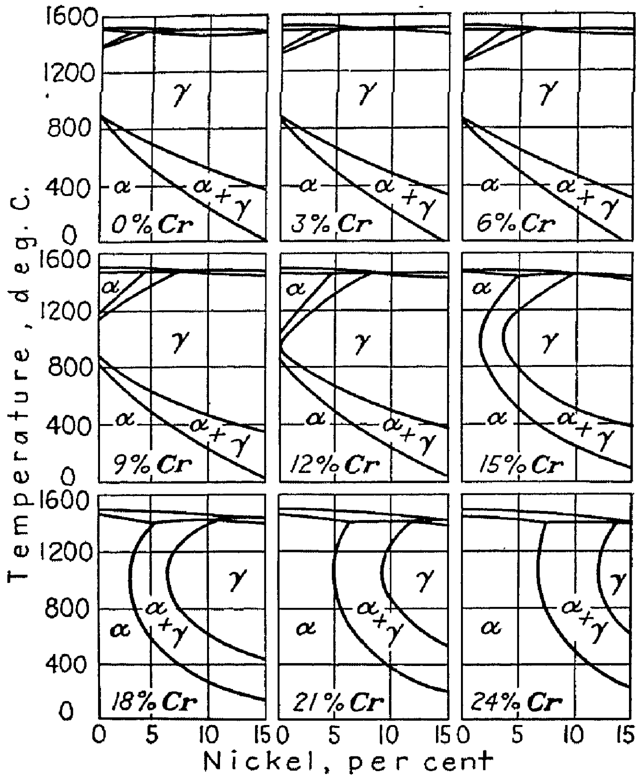

FIG. 81.—Semiquantitative constant-chromium sections. (*Bain and Aborn.*[517])

of the composition vertical with the solidus surface. No further change of structure takes place until the alpha-phase boundary is crossed, whereupon gamma phase separates (the first portion to appear contains perhaps 30 per cent nickel and 9 per cent chromium).

This process continues until the gamma-phase boundary is reached, at which alpha phase disappears and only gamma phase remains, containing 18 per cent chromium and 8 per cent nickel. This boundary is recrossed at a lower temperature, whereupon alpha phase reappears. Finally, the alpha-phase boundary is recrossed and at all lower temperatures alpha is the thermodynamically stable phase. In practice, the rates of the lower temperature transformations are so low that the structure stable at higher temperatures is preserved with relative ease by rapid cooling. Inspection of Fig. 84 shows at once why quenching from 1100°C. (2010°F.) is a suitable method to render a low-carbon 18-8 alloy wholly austenitic. This section shows also that increased nickel content increases rapidly the temperature range of stability of the gamma phase. Since rates of transformation are ordinarily very low below about 500°C. (930°F.), the gamma phase of an 18 per cent chromium, 15 per cent nickel alloy should be very persistent at room temperature.

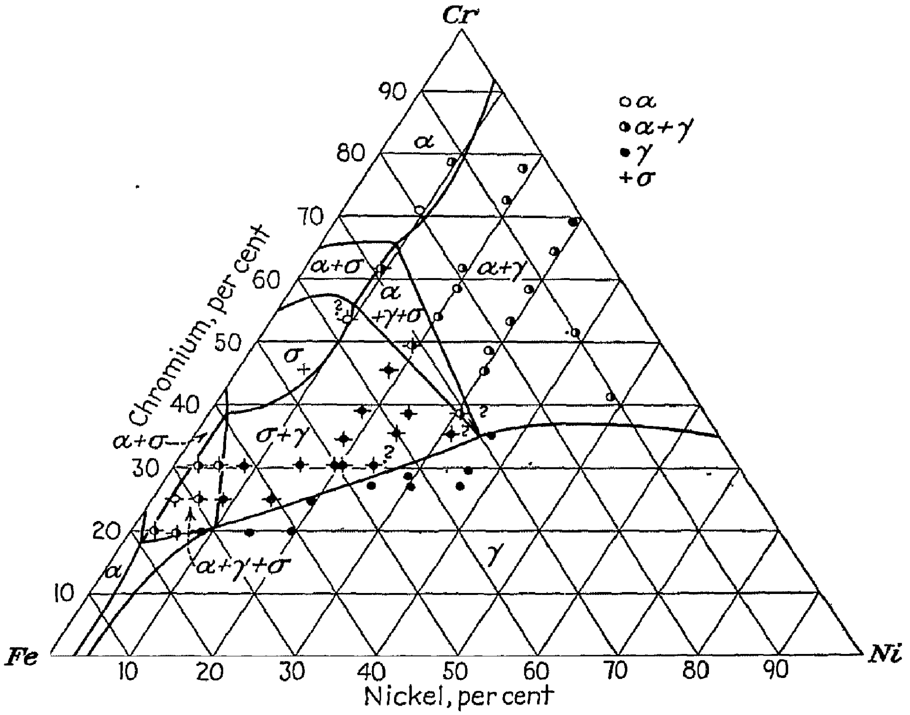

FIG. 82.—Isothermic section at 800°C. (1470°F.). (*Based on data of Schafmeister and Ergang* (507))

A section of the ternary diagram at 8 per cent nickel is given in Fig. 85. This shows that chromium cannot be increased much beyond 20 per cent (in 8 per cent nickel alloys, of course) if a wholly gamma-phase structure is required. The regions in which the sigma phase appears are not of importance in alloys given ordinary mill treatments; relatively long annealing at proper temperatures is required for its appearance.

Finally, it may be stated that a low-temperature horizontal section of the iron-chromium-nickel diagram for alloys cooled rapidly enough to prevent the appearance of the sigma phase (*i.e.*, at a rate comparable with that of ordinary mill operations) would be similar to Fig. 80 (page 269) for 1200°C. (2190°F.) in that only alpha, gamma, and alpha-plus-gamma fields would be shown. The only qualitative difference would be, of course, that the left-hand terminals would lie in the iron-nickel, rather than in the iron-chromium, side of the triangle.

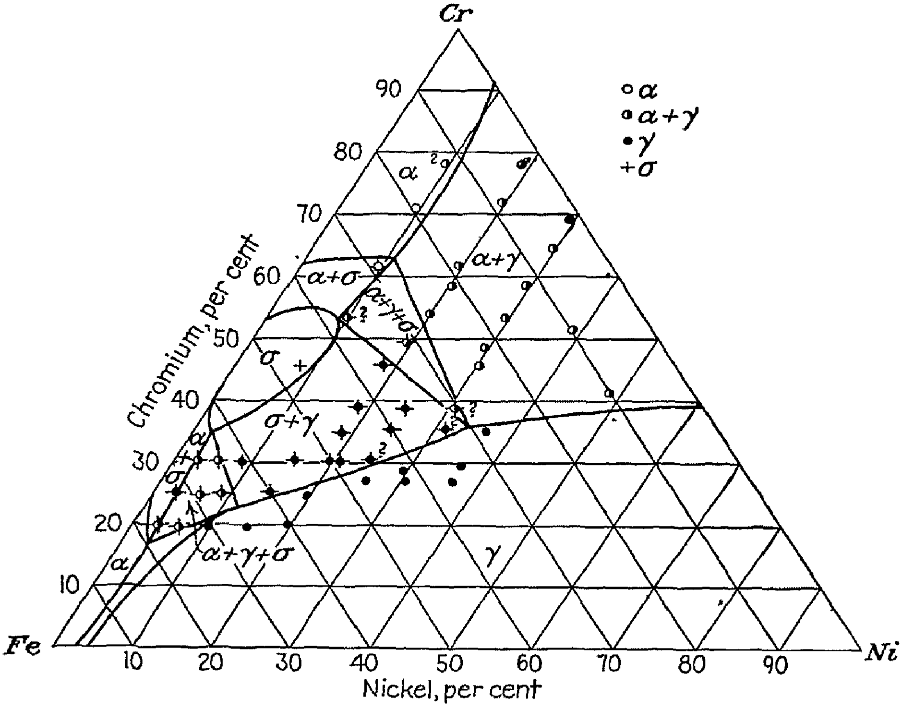

FIG. 83.—Isothermic section at 650°C. (1200°F.). (*Based on data of Schafmeister and Ergang.*(607))

145. The Effect of Carbon; Carbide Precipitation.—For certain practical reasons the effect of carbon on alloys of the 18 per cent chromium, 8 per cent nickel types is important, and the most lucid way of interpreting the behavior of such alloys containing carbon seems to be through the section of the iron-chromium-nickel-carbon diagram at 18 per cent chromium and

8 per cent nickel. That shown in Fig. 86 is only semiquantitative, because other than the solubility line for the carbide $(Cr,Fe,Ni)_4C$ (?) in the gamma phase—determined by Aborn and Bain⁽¹³²⁾—only line terminals lying in the iron-chromium-nickel plane are available. The upper portion of the diagram, however, constructed in accordance with phase theory, is consistent with the microstructural observations of Krivobok and Grossmann.⁽¹⁴⁹⁾

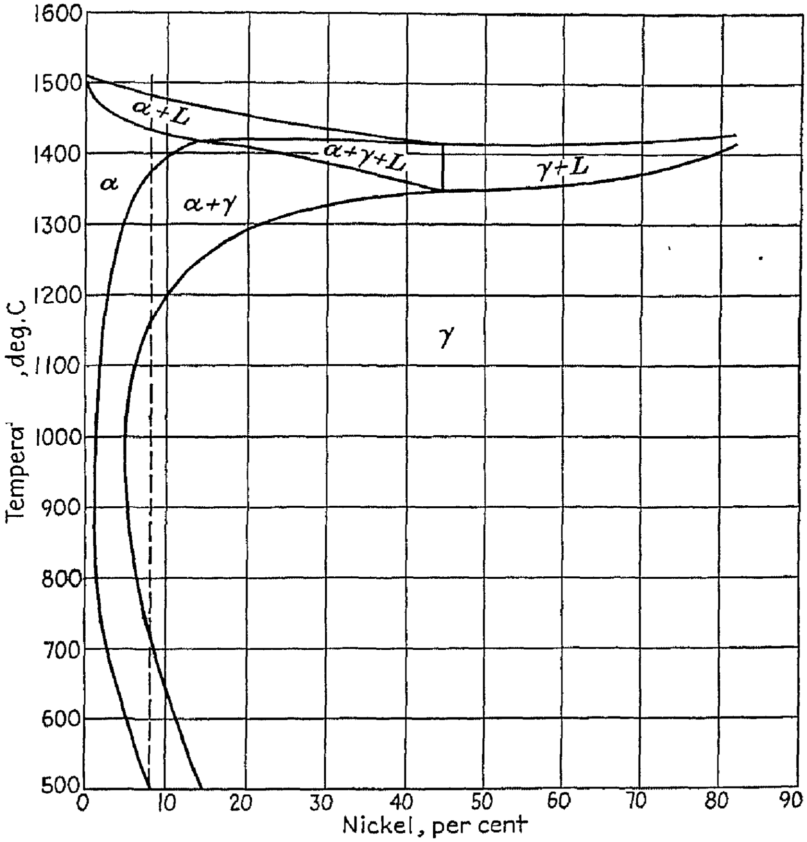

Fig. 84.—Section of the iron-chromium-nickel diagram at 18 per cent chromium.

There has been disagreement on the solubility of carbon in the gamma phase; for example, Strauss, Schottky, and Hinnüber⁽¹⁶¹⁾ cited a value of 0.04 per cent at 600°C. (1110°F.). Aborn and Bain, on the other hand, believed the solubility to be no more than 0.02 per cent at this temperature. The latter value seems more likely and was, therefore, selected for Fig. 86. The lower portion of the diagram shows that at temperatures approaching atmospheric, alloys in equilibrium contain no gamma phase, as is indicated elsewhere.

Early observers of steels of the 18-8 type believed them to be free from transformations in the solid state; for one thing, thermal analysis gave no sign of disturbance. Later it was discovered

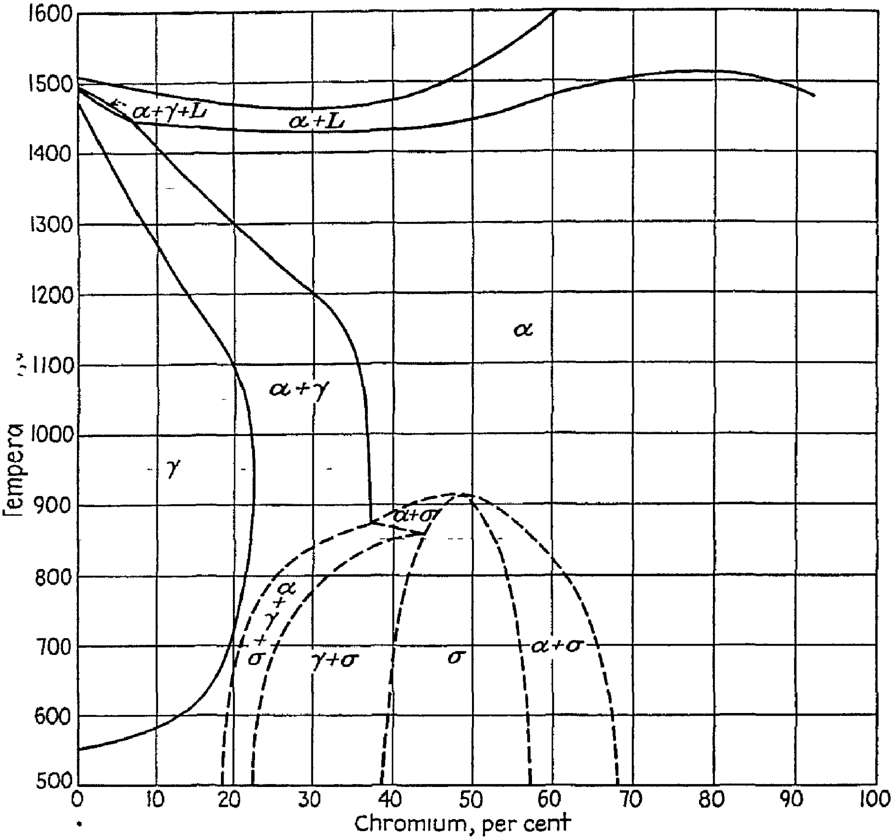

FIG. 85.—Section of the iron-chromium-nickel diagram at 8 per cent nickel.

that carbide appeared, usually in the grain boundaries, after such treatments as heating for some time in the range 300 to 900°C. (570 to 1650°F.) (see, for example, the photomicrographs of Becket and Franks(309)). Since the matter is of practical importance, it has received considerable attention; diagnoses were sometimes confused, and there is occasional evidence that confusion persists; consequently, it may be worth drawing attention to some of the implications—all in accord with experimental observations—of Fig. 86, restricting the description to alloys containing less than 0.015 per cent carbon. First, alloys quenched from temperatures approaching those of melting contain alpha phase; consequently, there is an upper as well as a lower temperature limit in the solid state for obtaining wholly gamma-phase material. Both the upper and lower temperature limits depend upon carbon content; for the grades of 18-8 currently manufactured, a quenching temperature of 1100°C. (2010°F.) is adequate. Second, free carbide must appear in all industrial alloys approaching equilibrium at the lower temperatures. However, reaction rates are very low; consequently, there is a strong tendency to preserve solubility values existing at higher temperatures. Cold work is effective in accelerating such delayed transformation. Thus, alpha phase usually appears, as well as carbide, after such treatment.

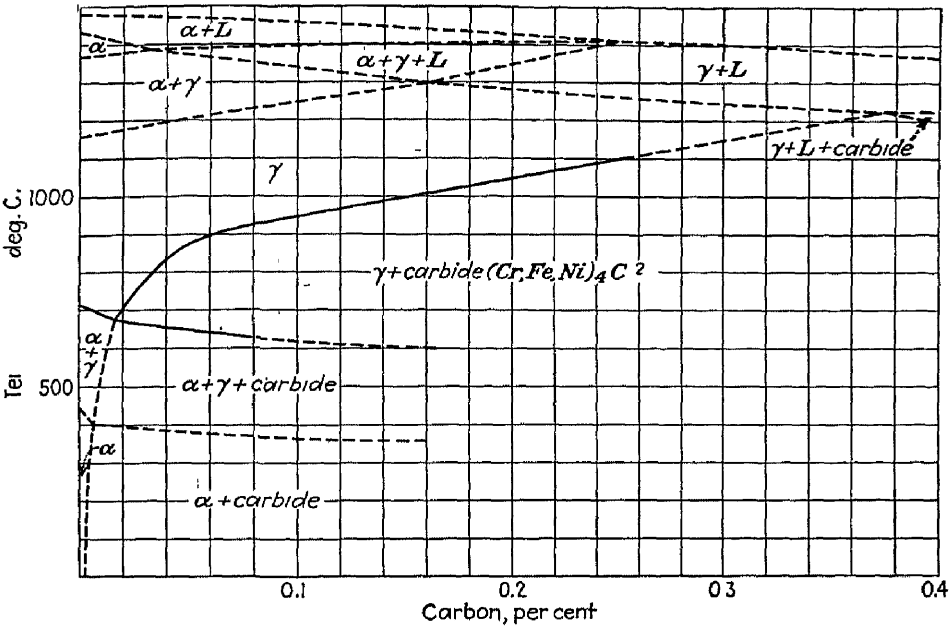

FIG 86.—Effect of carbon on the constitution of alloys containing 18 per cent chromium and 8 per cent nickel.

On the whole, it may be repeated that alloys of the 18-8 type are wholly austenitic and without free carbide only when quenched from high temperature. Carbide is precipitated relatively slowly in the lower carbon grades even during slow cooling through the 900 to 500°C. (1650 to 930°F.) range, a practice to be avoided if possible.

B. OTHER SYSTEMS

It is the purpose of this portion of the chapter to review briefly the information on other alloy systems of which iron and chromium are two components. Of these, the iron-chromium-manganese system has been subjected to more searching examination than the remainder.

146. The Iron-chromium-manganese Diagram.—Since manganese and nickel are similar in their effects on the transformations of iron, it is to be expected that their ternary systems with iron and chromium are similar, at least over certain ranges of concentration. Available data do not permit completion of the diagram even qualitatively, because nothing is known about the chromium-manganese diagram.

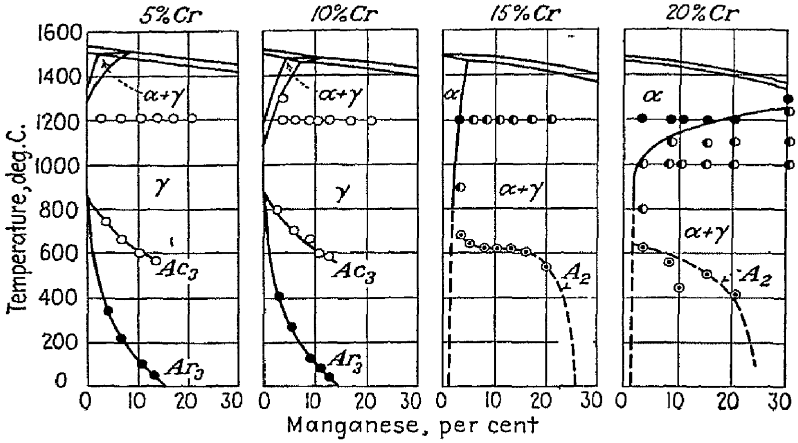

FIG. 87.—Constant-chromium sections of the iron-chromium-manganese diagram. (*Koster*.(281))

A few provisional partial sections, constructed by Köster,(281) are given in Figs. 87 and 88. That the intermediate iron-chromium phase (sigma) exists over wide concentration ranges in the iron-chromium-manganese system was found by Brühl,(419) Schmidt and Legat,(441) and, in greater detail, by Burgess and Forgeng.(490)

The last-named investigators selected for study 43 alloys prepared from ingot iron and low-carbon ferrochromium and ferromanganese Specimens were subjected to various heat treatments, then to microscopic examination and sometimes X-ray analysis. Supplementary information was gathered by hardness and magnetic measurements. Isothermic sections for 1000 and 650°C. (1830 and 1200°F.) are given in Figs. 89 and 90.

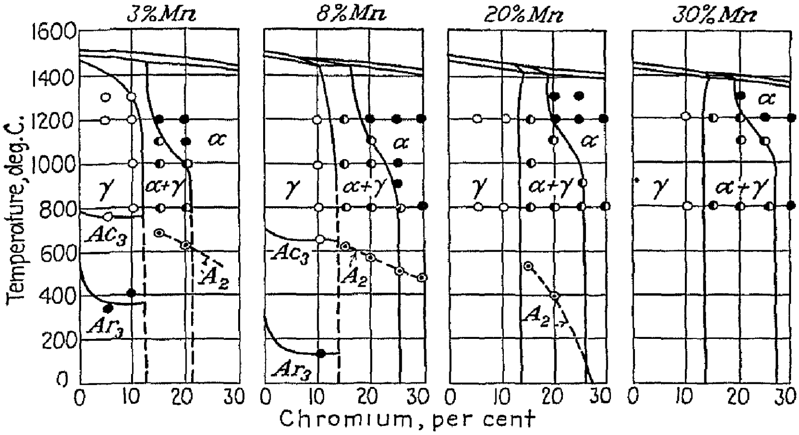

FIG. 88.—Constant-manganese sections of the iron-chromium-manganese diagram. (*Köster.*(281))

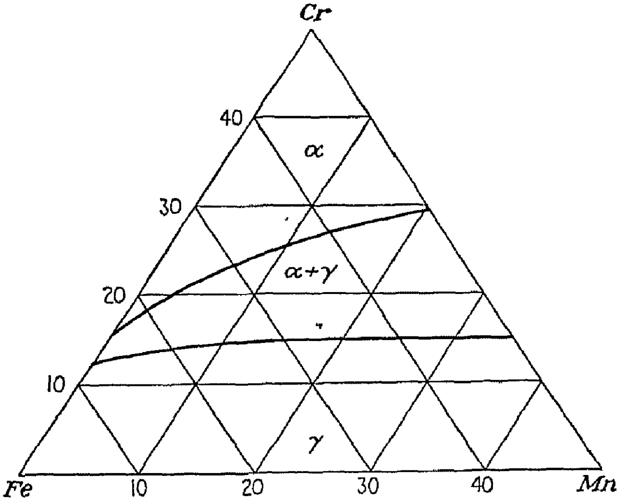

FIG. 89.—Isothermic section of the iron-chromium-manganese diagram at 1000°C. (1830°F.). (*Burgess and Forgeng.*(490))

The latest information was supplied by Schafmeister and Ergang,(508) who used methods similar to those of Burgess and Forgeng. Results are summarized as an isothermic section at 700°C. (1290°F.), shown in Fig. 91. A wider range of concentrations was studied by Schafmeister and Ergang than by

Burgess and Forgeng; consequently, it was possible for the former to construct a somewhat more complete section. In

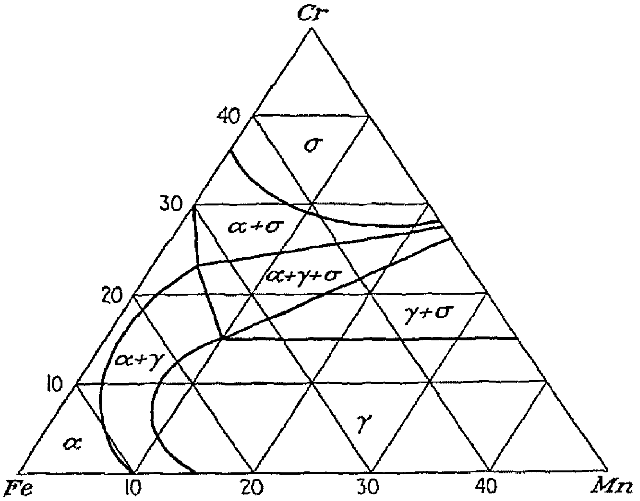

FIG. 90.—Isothermic section of the [illegible] diagram at 650°C (1200°F.). (B[illegible]

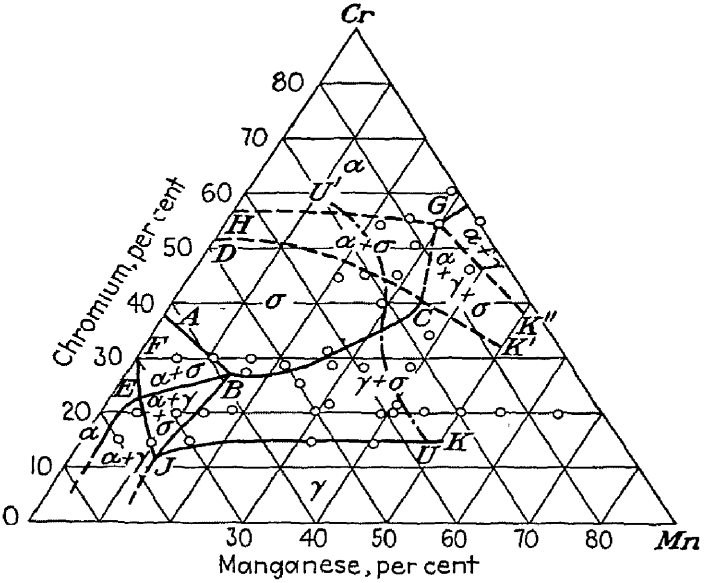

FIG. 91.—Isothermic section of the [illegible] diagram at 700°C. (1290°F.). (Sch[illegible]

comparable ranges of concentration, certain differences appear, chief among which is that Schafmeister and Ergang showed the sigma-phase corner of the first three-phase triangle to exist at about 15 per cent manganese, whereas extrapolation of Burgess and Forgeng's diagram indicates a value of about 25 per cent.

In passing, it may be noted that Burgess and Forgeng differed from other workers in that they advanced the opinion that "the sigma phase results from an allotropic transformation of a highly saturated ferrite and is not considered to be an intermetallic compound."

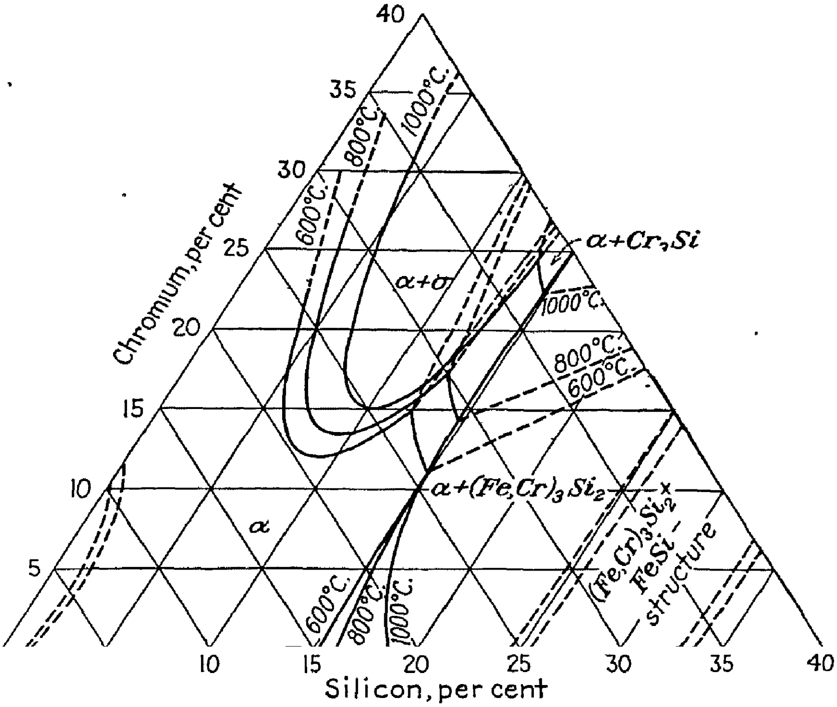

FIG. 92.—Incomplete isothermic sections of the iron-chromium-silicon diagram at 600, 800, and 1000°C. (1110, 1470, and 1830°F.). (*Andersen and Jette.*(416))

On the whole, quantitative knowledge of the iron-chromium-manganese system is far from complete.

147. Iron-chromium-manganese-carbon Alloys.—According to Kluke,(462) who investigated three series of cast alloys containing 0.35, 0.6, and 1 per cent carbon, 30 per cent chromium, and up to 20 per cent manganese, the following structures appear:

1. Up to 10 per cent manganese, a mixture of alpha phase and carbide.
2. From 10 to 15 per cent manganese, sigma phase in addition.
3. With more than 15 per cent manganese, sigma phase and carbide.

Annealing at 600 to 1000°C. (1110 to 1830°F.) for 100 hr. had no observable effect on the manner of participation of the sigma phase.

148. The Iron-chromium-silicon Diagram.—Since silicon forms a number of compounds with both iron and chromium, the iron-chromium-silicon diagram is complicated. Investigators of the system have been few; Denecke(67) examined about 25 alloys containing up to 30 per cent each of chromium and silicon by thermal and microscopic analyses, with not very reliable results; and Andersen and Jette(416) conducted an extensive X-ray analysis of alloys prepared from high-purity silicon, electrolytic chromium, and carbonyl iron. Results in the form of three incomplete isothermic sections at 600, 800, and 1000°C. (1110, 1470, and 1830°F.) are given in Fig. 92. These data led also to a tentative complete section at 1000°C., shown in Fig. 93.

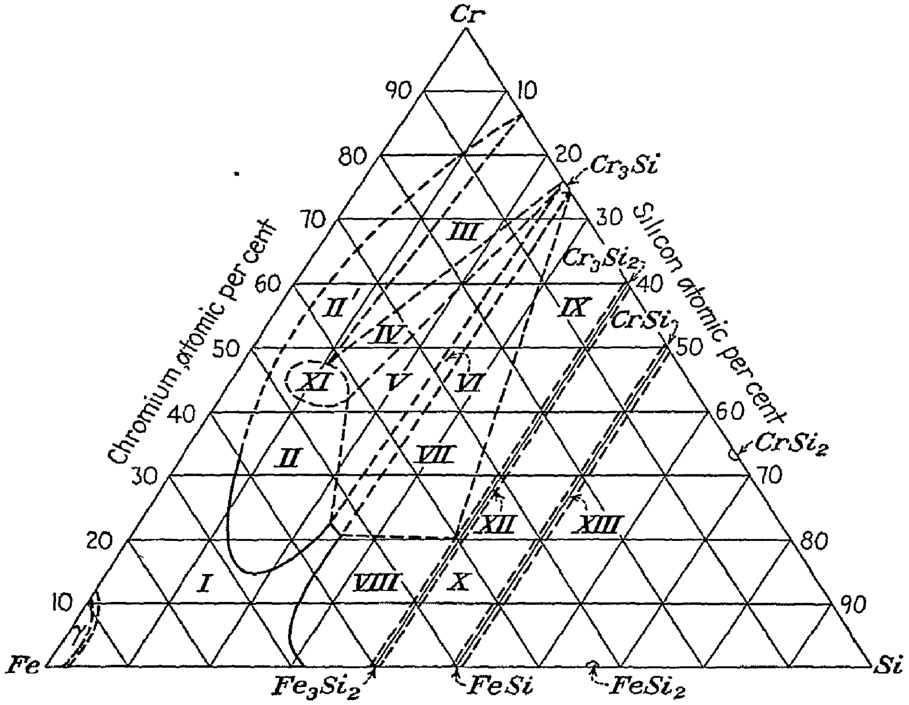

Fig. 93.—Isothermic section of the iron-chromium-silicon diagram at 1000°C. (1830°F.). (*Andersen and Jette.*(416))

149. The Iron-chromium-phosphorus and Iron-chromium-sulphur Systems.—For completeness it may be stated briefly that iron-chromium-phosphorus alloys containing up to 28 per cent phosphorus were investigated by Vogel and Kasten.(514) Results are given as a series of projections and sections of the ternary diagram. Results for the iron-chromium-sulphur diagram are given in a similar manner by Vogel and Reinbach.(478)

Additions of phosphorus and sulphur to iron-chromium alloys are of industrial importance, but solubility measurements were not made in composition ranges of interest from this standpoint. The sections, therefore, indicate qualitatively only that phosphides or sulphides appear upon additions of fractional percentages of phosphorus or sulphur; this, of course, has been a matter of practical observation for some time. The diagrams are not reproduced here because of this limitation.

C. AUTHORS' SUMMARY

1. The qualitative precision of the important iron-chromium-nickel diagram is such that further change is unlikely. Quantitatively, however, there is less precision than might be desired; reaction rates over certain ranges of temperature and concentration are so low that conditions of equilibrium are difficult to approach. Nevertheless, results for non-equilibrium conditions are highly useful in that they permit simple interpretation of the behavior of industrial alloys.
2. Iron-chromium-nickel alloys of the 18-8 group are austenitic at room temperature because of the persistence of the gamma phase rather than thermodynamic stability. Cold work accelerates transformation to the alpha phase.
3. Many iron-chromium-nickel alloys of the "highly alloyed" group when approaching equilibrium contain the intermediate sigma phase of the iron-chromium system. This leads to an unusual construction in the ternary diagram, because the phase appears only over a limited temperature range in the solid state. The boundaries of the regions in which sigma phase participates are yet to be established with precision. Since the rate of transformation to sigma phase is low, structures existing at high temperature are preserved easily at room temperature. Transformation may proceed, however, in highly alloyed materials in elevated-temperature service. Consequently more knowledge of the concentration ranges and of transformation rate would be useful.

4. The presence of free carbide in alloys of the 18-8 group may be objectionable from the standpoint of greatest resistance to corrosion, consequently, the conditions under which this phase appears are important. These are most easily inferred from inspection of the diagram given on page 275. There are few data upon which to base such a section, but its qualitative correctness is likely. In addition to the matter of carbide precipitation, Fig. 86 shows at once the reason for the practical observation that 18-8 alloys are certain to be wholly austenitic only when quenched from relatively high temperatures, *i.e.*, from the neighborhood of 1100°C. (2010°F.).

5. The iron-chromium-manganese diagram has much in common with the iron-chromium-nickel diagram; among other things, their sigma-phase regions are similar. It is not possible, however, to carry the construction of this diagram to even qualitative completion, for, among other things, the chromium-manganese diagram is unknown. Because of the lack of industrial interest in the iron-chromium-manganese alloys further work is, for the present, improbable.

6. Of the other ternary systems of which iron and chromium are components, that containing silicon has been subjected to extensive X-ray analysis. Those containing phosphorus and sulphur have been examined by microscopic and thermal analyses.

CHAPTER X

MANUFACTURE AND FABRICATION OF AUSTENITIC CHROMIUM-NICKEL STEELS

Melting and Working—Miscellaneous Fabricating Operations—Welding—Authors' Summary

In the industrial development of the austenitic chromium-nickel steels two requirements were considered of primary importance. The first was a high degree of corrosion resistance. As is well known, at least 12 per cent chromium is necessary for substantial resistance to oxidizing media; for more universal resistance, however, the chromium should be 18 to 20 per cent. The second requirement was satisfactory strength, ductility, and formability at normal temperatures and relatively high strength at elevated temperatures. This was best secured by an austenitic material; hence, the addition of considerable nickel was necessary.

While Strauss(56) investigated a wide range of chromium-nickel steels, including one which contained 20 per cent chromium and 7 per cent nickel with relatively high carbon, Hatfield in his investigations noted the particular properties of alloys containing 18 per cent chromium and 8 per cent nickel and proceeded to develop these on an industrial scale. He reported his work a few years later(86) and emphasized the point that alloys containing 18 per cent chromium and relatively low carbon must contain at least 8 per cent nickel in order to produce a definitely austenitic state under usual manufacturing conditions.

In the past fifteen years, a large amount of work has confirmed Hatfield's findings that the low-carbon 18-8 type is the most suitable composition for a wide variety of special applications involving corrosion both at normal and at elevated temperatures. There is, however, a tendency, especially in the last few years, to increase slightly both the chromium and nickel percentages.

For corrosive conditions so severe that the usual 18-8 material is unsatisfactory, a steel containing 20 to 26 per cent chromium and 10 to 14 per cent nickel has been developed. It is remarkably resistant to oxidation and corrosion by some atmospheres at temperatures as high as 1100°C. (2010°F.). For other special applications, a steel containing 24 per cent chromium and as much as 20 per cent nickel is used; the bulk of the production of the austenitic corrosion-resistant alloys is, however, of the 18-8 type.

A. MELTING AND WORKING

Little can be added to the general discussion in Chapters II and III of the melting and working of the austenitic steels. Most of the tonnage of these materials is melted in the electric-arc furnace from high-grade low-carbon scrap and low-carbon ferrochromium; arc or induction furnaces are used for remelting scrap. Ingots are usually large and are hot worked with much less difficulty than the plain high-chromium steels of the medium- and high-carbon grades. Wrought products of high chromium-nickel steels are also readily cold worked.

150. Melting Practice for Ingots.—As brought out in Chapter II (pages 19 to 21 and 24), the important point in melting austenitic chromium-nickel steels is that the addition of nickel introduces no complications into the practice; nickel may be added with the charge as the metal or as nickel-steel scrap at any time during refining.

The chromium is added as the low-carbon ferroalloy after the metal is deoxidized as much as possible by the silicon in the slag. Exceptional care should be exercised all through the refining period to keep oxidation to a minimum and to degasify as completely as possible; any blow holes in the ingot do not weld in hot working and persist as laps and seams in the finished product.(189,307) Low-carbon (0.06 per cent) ferromanganese and ferrosilicon (75 per cent silicon) are used for the final deoxidation. A complete log of a 15-ton heat of austenitic chromium-nickel steel, representative of current arc-furnace practice, is given in Table 1, page 24.

The remelting of high-chromium scrap in the high- or low-frequency induction furnace, in the electric-arc furnace, and in a small open-hearth furnace, as described previously (pages 33 to 35), applies in all its details to the remelting of austenitic chromium-nickel steel scrap. The induction furnace is especially adapted to scrap melting as it is relatively easy to maintain the carbon at a low percentage. After melting, the bath is generally superheated, deoxidized, and held in the crucible under low power for a brief period before pouring. It is important that the slag viscosity be correct since the violent stirring in the melt, while the power is on, may be responsible for slag inclusions in the metal.

The problems connected with remelting low-carbon chromium-nickel scrap in the induction furnace have been discussed recently by Smith,(245) Bigge,(489) and Farnsworth and Johnson.(492)

151. Manufacture of High Chromium-nickel Steel Castings.—Owing to their heat and corrosion resistance, the austenitic chromium-nickel steels are widely used as castings. They are, however, difficult to handle in the foundry; it is necessary to pour them into dry-sand molds having specially prepared surfaces so that the surface of the casting will be of satisfactory quality. Many precautions are necessary(494); shrinkage is higher than for carbon steel; hence, there is danger of shrinkage cracks at the corners and in other locations where there are abrupt changes of section. In complex castings, chills are commonly employed. Pouring temperatures must be controlled within narrow limits if the section is complex; if the steel is poured too cold, the castings are liable to contain laps, seams, and cold shuts; and if it is poured too hot, there is a tendency for the sand to fuse to the surface.

Although an appreciable tonnage of cast low-carbon 18 per cent chromium, 8 per cent nickel steel is made, casting difficulties are especially apparent with this grade; hence, there is a tendency in the United States to increase the chromium, nickel, and carbon contents.* According to Wilcox(411) and Thum,(511) typical compositions of the austenitic steels that are favored for heat- and corrosion-resisting castings are: 20 to 24 per cent chromium and 10 to 12 per cent nickel, or 28 to 29 per cent chromium and 9 to 12 per cent nickel, both with about 0.20 to 0.30 per cent carbon. A specification for such castings, recently adopted by the paper manufacturing industry, requires a minimum of 20 per cent chromium and 9 per cent nickel with a maximum carbon content equivalent to one one-hundredth of the chromium content. Higher nickel steels, containing 28 to 38 per cent nickel and 15 to

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* Hatfield and Monypenny both advised that no such tendency is evident in England (private communications).

20 per cent chromium, are also used for heat-resisting castings.(511) In view of their high nickel content, such materials are discussed in "The Alloys of Iron and Nickel."(503)

The low-carbon 18-8 steel is usually melted in the basic electric furnace, under two slags.(63) Most of the tonnage of the higher chromium-nickel material containing about 0.20 per cent carbon is melted in small acid-lined electric furnaces of the Héroult type; only one slag is necessary,(239) and the ferrochromium which is used can contain somewhat more carbon than is permissible for low-carbon alloys. Recently centrifugal castings of low-carbon 18-8 have been made. Few details of technique have been published. The molds are usually preheated to about 500°C. (930°F.), as cold molds, especially if made of steel, cause longitudinal cracks in the casting (504) In general, high pouring temperatures must be used; but despite this, the castings are fine grained. Centrifugal castings are frequently used for seamless tubes.

It is common practice after pouring the austenitic chromium-nickel steel castings, to anneal them by heating to about 1000 to 1100°C. (1830 to 2010°F.) followed by water quenching, air blasting, or air cooling as the shape and size of the casting permit. If the castings are to be descaled, they are immersed in a solution of about 6 5 parts by weight of rock salt in 10 per cent sulphuric acid or in a solution containing about 8 per cent nitric acid and 2 to 3 per cent hydrofluoric acid. Each solution is heated to about 60°C. (140°F.). Another method of descaling consists of sand blasting with subsequent treatment in a 20 per cent nitric acid solution to remove foreign matter from the surface. (The descaling of wrought products is discussed on pages 288 to 289.)

It is difficult to remove the gates and risers from austenitic chromium-nickel steel castings. In some cases these parts are cut off with an oxyacetylene cutting torch by means of the zigzag or steel-rod technique. In other instances they are removed by sawing or by cutting with a rubber-bonded abrasive wheel approximately ⅛ in. thick. Finished castings are ground with standard grinding wheels and machined as required.

Castings of the chromium-nickel steels can be welded by the oxyacetylene or electric process. The same principles employed in welding wrought products are also applied to assure welds of satisfactory quality. Welding is used to a great extent to repair defects.(511)

152. Hot Working.—The hot working of low-carbon chromium steels containing 12 to 30 per cent chromium is discussed in detail in Chapter III. Nickel introduces into the rolling practice no complications worthy of extended discussion except the need for more power, owing to the higher strength of the nickel-containing steels at rolling temperatures; hence, it is only necessary to give here such minor details as apply specifically to the austenitic materials.

For rolling bars, fluted ingots up to 20 in. in diameter and weighing up to 10,000 lb. are preferred; for sheet and strip rolling, a rectangular mold varying in size up to 17 × 20 in. is usual. Conventional hot tops are used.

Ingots are occasionally forged(298) or hot pressed, but it is general practice to hot roll directly from the ingot. The hot rolling as described by Johnson and Sergeson(230) is carried out at initial temperatures of about 1200°C. (2190°F.) and is not continued at temperatures much below 900°C. (1650°F.), except if a cold-working effect is desired. However, hot working within the temperature range between 900 and 600°C. (1650 and 1110°F.) tends to produce cracks and tears.

The austenitic steels are much stronger than ordinary carbon steels at the temperatures employed in forging and rolling; thus, more power is required to deform them. This decreases the amount of work that can be done in a given pass and necessitates reheating a greater number of times. In addition, it decreases the width of sheets or strips that can be hot rolled to a uniform gage with the usual mill.

When piercing seamless tubes of these steels was first attempted, difficulties were numerous. According to Hamilton,(318) at least part of the trouble was due to high oxide content. This has now been overcome by improvement in melting and rolling practice. Steels that are fully austenitic at the piercing temperature are preferred for this operation. To make seamless tubes with 8-in. outside diameter, the initial piercing temperatures should be between 1150 and 1200°C. (2100 and 2190°F.).

Various structural shapes of the 18-8 steels have been manufactured, although even at present the production of relatively large I-beams is not wholly successful. The metal is readily rolled into rods ¼ in. in diameter which are coiled into 250-lb. coils. It is also readily worked into hexagonal nuts, bolts, rhomboid pins, and flat side washers.

153. Pickling.—In most instances hot-rolled 18-8 and 24-12 type steels are heat treated prior to pickling. This consists of rapid cooling (quenching or usually air cooling) from 1000 to 1150°C. (1830 to 2100°F.). It is necessary to provide maximum corrosion resistance during the pickling operation, and failure to heat treat may lead to excessive metal loss in pickling as well as to permanent damage to the steel owing to grain-boundary attack by the pickling solution.

Many different acid solutions are used for pickling;(405) one of these contains 10 to 15 per cent sulphuric acid with 5 to 25 per cent hydrochloric acid; another, more efficient one, contains 6 to 10 per cent nitric acid with up to about 3 per cent hydrofluoric acid; each of them is heated to about 60°C. (140°F.). Monypenny(191) cited a solution of 5 to 10 per cent sulphuric acid with a restrainer or inhibitor consisting of 1 part of sizing glue, 1 part of concentrated sulphuric acid, and 2 parts of water. One part of restrainer is added to 100 parts of the pickling solution, and the pickling is carried out at 60 to 70°C. (140 to 160°F.). Hydrochloric acid is also used, at strengths varying from 20 to 50 per cent, at 70 to 90°C. (160 to 195°F.). To produce a silvery gray surface, Monypenny recommended a pickling bath of 3 to 5 per cent nitric acid and 1 per cent hydrochloric acid to be used at room temperature, or 25 per cent hydrochloric acid, 5 per cent nitric acid, and 0.5 per cent restrainer by volume to be used at 60 to 70°C. (140 to 160°F.). He added that the bath distinctly attacks the steel so that sheets and plates that are placed on edge are kept in motion. A small quantity of nitric acid should be added from time to time so that the bath finally has a passivating action, and dilution should be avoided to prevent pitting. He suggested an average pickling time of about 20 min. Monypenny emphasized the need for passivation as a general procedure following any pickling bath, although he implied that the nitric acid in the aforementioned bath acts as a passivating agent.

Electrolytic pickling has been variously tried but seems to have found little industrial application. Electrolytic pickling with phosphoric acid solutions yields a particularly good surface when applied to material with relatively thin scale; the phosphoric acid pickling bath has also been used successfully without the aid of electrolysis.

Surface brightening by electrolytic pickling of articles that are already cleaned is mentioned in passing since it is not a true pickling operation. Various solutions, generally containing chromium salts, are used for this purpose. The resulting surface looks almost as if it were tinned. As yet the process does not seem to have been applied industrially.

Frequently, in removing the scale from heavier sections, such as sheet bars, plate bars, billets for seamless tubes, or other heavy articles, sand blasting is employed. This method is useful prior to inspecting billets for rolling into finished products because it discloses such defects as scabs, checks, cracks, and seams, which must be removed by grinding or chipping before the steel is finish-rolled.

154. Cold Working.—Austenitic chromium-nickel steels are cold worked industrially, but—because of their tendency to work harden(140,191)—considerably more power than for carbon and low-alloy steels and special mills are required. In the production of cold-rolled sheet or strip, a cluster four-high mill or the equivalent is used. It is general practice to start rolling with fully softened material of 12-gage thickness, and to use at least two passes for a 30 per cent reduction in cross-sectional area. The material is then resoftened by heat treatment, pickled, and again cold rolled. Usually, in producing light-gage strip or sheet, a comparatively large number of cold-rolling passes is required, and the steels work harden to such an extent that there are much greater practical limitations to the width that can be cold rolled to uniform gage than is the case with carbon steels. It is reported that work hardening in cold rolling is reduced by applying heavy tension to the material as it comes from the rolls. This avoids slippage and freezing of the steel to the roll surface. The chromium-nickel steels are readily fabricated into cold-drawn seamless tubes, bars, and wire,(358,400) and, as in the case of sheet or strip, it is possible to secure a reduction of approximately 30 per cent in cross-sectional area before softening is required. In cold drawing these articles, it is necessary to use a lubricant to prevent excessive wear on the dies and seizure Lead or lead-tin alloys are used as in the drawing of plain chromium steels described in Chapter III.

The tendency of the 18-8 steels to work harden is illustrated by a comparison of the hardness of 5⁄16-in. diameter rods of ordinary 0.30 per cent carbon steel, plain 18 per cent chromium steel, and an 18-8 steel, as annealed and after reducing the diameter of these rods to 1⁄4 in. by cold drawing.(369) The Brinell hardness of the 0.30 per cent carbon steel increased from 170 to 196, approximately 15 per cent; that of the 18 per cent chromium steel increased from 149 to about 200, about 35 per cent; and that of the 18-8 steel increased from 135 to 293, about 117 per cent. The contrast is striking and is open to question as a generalization only insofar as the increased hardness of the plain chromium steel is concerned. Monypenny(191) found that the hardening by cold work of plain chromium steels is practically the same as that of carbon steels.

B. MISCELLANEOUS FABRICATING OPERATIONS

The austenitic chromium-nickel steels are subjected industrially to a number of fabricating operations including polishing, cold forming, and machining; they are joined by various methods such as riveting, soldering, and welding. In polishing and cold forming, the strong tendency of the material to work harden is of great importance.

155. Grinding and Polishing.—Articles of 18-8 steel with polished surfaces have found comparatively wide application.(158) The manufacturers have adopted finishes that vary from those usual for hot-rolled, annealed, and pickled articles, to those equivalent to a mirror in polish and luster. Most frequently, these finishes are applied to flat products, and special grits or pumice with fiber wheels are employed to obtain the desired surface. The operation is not essentially different from the surface preparation of plain chromium steels described in Chapter III. However, certain details particularly pertinent to the austenitic steels are given here. Prior to polishing, the flat products are either cold rolled or ground. The term grinding usually applies to a dry cutting operation, while polishing generally involves a wet operation in which grease or oil is employed. The experience has been that grits are satisfactory up to the No. 180 size, but from there on either the Turkish or black emery or fused alumina is used. The most satisfactory buffing compounds are based on aluminum oxide or chromium oxide, and to obtain the best luster on a polished sheet it is preferable to use the alumina first and to follow this with a buff on a separate wheel.

156. Cold Forming and Machining.—Among the ordinary cold-forming operations performed on these steels are shearing, blanking, punching, forming, drawing,(247) spinning, drilling, sawing, threading,(287) tapping, and turning. Unless the shearing blades have sharp edges and are closely adjusted, the metal will be severely cold worked by compression or bending over the bottom knife edge, and undue strain will be put upon the shearing blades. In shearing ordinary steel, the knife cuts only a part of the way through the section which then breaks, but in shearing the 18-8 steel, the blade must cut entirely through the section. It has been estimated that for shearing a given thickness of 18-8 steel approximately twice the power is required as for shearing carbon steel. When blanking and punching the austenitic steels, it is also necessary to maintain close clearance between the punch and the die.(284) If the clearance is too great, the metal will be drawn over the edge of the die and work hardened so that serious damage may be done to the section being punched as well as to the punch and die. It is advantageous to have a clearance of between 0.001 and 0.0015 in. between the die and the punch for gages below a thickness of 0.035 in., but for the heavier sections a clearance of between 0.0015 and 0.002 in. is recommended.

A Rockwell *B* hardness value of 85 is specified to assure successful forming and drawing of 18-8 steel, although in severe drawing operations the hardness should be about 80 to permit the material to be drawn approximately 40 per cent without danger of rupture. If additional drawing is required, it is best to resoften(246) and pickle the article. The use of a heavy lubricant is frequently necessary. White lead thinned with linseed oil to give a consistency of 600-W engine oil is one of the compounds recommended for use in deep drawing heavy-gage material.

As in the case of other cold-forming operations, the only difficulty that is encountered in spinning results from excessive stiffness developed by cold working. The speed of the spinning operation should be 25 to 50 per cent less than that employed in spinning copper, and considerably more power should be applied. The use of a lubricant such as a compound of white lead and linseed oil has a decided bearing on the final result. Although these steels are soft initially, it is impossible to spin them in one operation to the depth to which copper is spun. This is again due to the hardening by cold working. It is necessary to limit the amount of cold work on a given section to prevent the development of tears in the body as well as at the edges of the section being spun. This is done by heat treating and pickling at proper intervals.

The most satisfactory steel for severe spinning operations is one in which the nickel content of the usual 18-8 is increased to about 12 per cent, keeping at the same time a carbon content of about 0.10 per cent. This steel has considerably less tendency to work harden than the regular 18-8 material. It is also suited for severe deep-drawing operations.

Drilling, turning, sawing, and threading operations are usual, but certain precautions are necessary, again owing to work hardening. The tools used for drilling and turning(174,344) must have keen edges, and once the cut is started, it is continued to completion. The high-speed steel drill is ground slightly flatter than usually recommended for work on carbon steel, and the austenitic steel should not be punched before drilling. The speed of these operations is controlled so that the cutting edge of the tool is free of cut metal at all times. Speeds used are somewhat lower than ordinarily used on carbon or low-alloy steels. High pressures with dull tools result in hardening that practically stops the cutting. As with other types of steel, free-machining varieties containing high sulphur are essential for maximum machinability. The high-sulphur 18-8 type and a free-machining selenium 18-8 material are discussed in Chapter XIII.

Seamless tubes of austenitic chromium-nickel steels have been employed widely in oil refining. The forming operations ordinarily required for the installation of tubing in equipment of this kind are expanding, rolling, flanging, Van Stoning, and upsetting. If the available apparatus is not powerful enough to perform these operations at room temperature, temperatures between 1000 and 1200°C. (1830 and 2190°F.) are employed.

Under no circumstances should the work be done between about 600 and 900°C. (1110 and 1650°F.), and temperatures between 300 and 600°C. (570 and 1110°F), while helpful in reducing the required power, do not leave the steels in the best condition for future high-temperature service.

157. Riveting and Soldering.—Riveting, caulking, soft soldering, and silver soldering are used successfully in joining parts of 18-8 steel. Brazing is not generally recommended as the temperatures required for this operation are within the range that detrimentally affects resistance to corrosion. The damage cannot be remedied by heat treatment as the brazing metals melt at the required temperatures.

Little trouble is encountered in riveting(121); but it is important to heat the rivets to approximately 1100°C. (2010°F.) and finish drive them before the temperature drops below about 975°C. (1785°F.). If lower temperatures are employed, the corrosion resistance of the steel is adversely affected, and it may be impossible to close the rivets properly. After riveting, both the inside and outside of the joint are caulked In light-gage construction the caulking tool is opposed by a backing-up bar. Practice has shown that a tighter joint is obtained by the use of a pressure riveting system. Cournot and Baudrand (420)recommended the use of 18-8 rivets for any alloy-steel structure which is to be exposed to sea-water corrosion. These investigators found a very small loss in strength in such structures after corroding 1680 hr. in artificial sea water at 20°C. (70°F.).

In soft soldering, a flux that etches the surfaces to be soldered is essential. A number of such fluxes are available. Most of these tin the surface of the metal in addition to removing oxide or other foreign particles. Polished surfaces are relatively resistant to hydrochloric acid which is the base of most of the soldering fluxes, and it is advisable to roughen the surfaces to be soldered before the application of the flux The soldering iron or tool used for 18-8 is generally larger than that used for ordinary steels. Cover plates of copper are employed to prevent thin sheets of 18-8 from buckling. After soldering, it is important to eliminate all flux on the metal by careful washing with soap and water or ordinary soda to avoid subsequent corrosion. Soldering is never relied upon for a high-strength joint, but it is used for sealing a high-strength joint produced by spot welding or riveting. The chromium-nickel steels can be silver soldered to each other or to carbon steel or copper. In this operation, a flux made of fluorides and borates serves well. However, as in soft soldering, it is essential that the last traces of the flux be removed by washing to prevent further attack of the metal.

C. WELDING

Welding is an important method of fabricating austenitic chromium-nickel steels, not only in the construction of streamlined trains, but also for many other and equally important applications which have not aroused so much public interest. The wrought low-carbon grades can be welded by any of the well-known processes except hammer welding; *i.e.*, they can be joined by electric welding—including metallic-arc, carbon-arc, resistance, seam, butt, spot, or line welding—or by gas welding by the oxyacetylene or the atomic hydrogen process. These methods have been discussed pro and con in a large number of articles, some of which(96,103,129,161,164,205,304,327) deal with the subject broadly. For a concise summation of welding the various austenitic chromium-nickel grades, chapters by Miller,(382) Bibber,(352) Ragsdale,(397) and Smith(403) in "The Book of Stainless Steels" and especially the recent review and compilation by Spraragen and Claussen(527) are recommended.

158. General Precautions in Welding.—Certain physical characteristics of the austenitic steels are very important in all of the welding processes. Those having to do with the weld proper are outlined here; the effect of the welding heat on the steel in the zones adjacent to the weld is a story in itself and is discussed elsewhere.

The coefficient of linear expansion of the austenitic chromium-nickel steels is about 50 per cent greater than that of plain carbon steel, and the thermal conductivity is only about one-third of that of unalloyed material.(129,227,502) This makes it necessary, according to Spraragen,(129) to use a smaller tip in gas welding and lower current values in arc or resistance welding; furthermore, it is advisable to use copper backing slabs to keep the temperature down and reduce the expansion. The use of proper clamps and jigs is the most important factor in the production of good welds.

The electric resistance of austenitic chromium-nickel steels is about six times that of mild steel, and this value is approximately doubled if the material is severely cold worked. This, however, is an advantage in resistance welding,(397) especially of cold-rolled sections which have bright, scale-free surfaces.

159. Gas Welding and Cutting.—Sound, ductile welds are readily made by oxyacetylene welding,(96,103,129,164,192,382) although electric welding is more widely used for material ⅛ in. or more in thickness. For light gages, gas welding is preferable.(103,129) For butt welding thin-gage sheets (16 gage or less), the best results are obtained if the material is flanged and free from oxides or scale. The use of jigs and chill plates of copper minimizes warping. Uncoated welding rods, which have a diameter about the same as the thickness of the sheet to be welded, are used with a flux that dissolves the oxide formed.(129,502)

Frequently a flange about 1/16 in. wide supplies enough metal to fill the joint, thus making the use of a welding rod unnecessary. Miller(382) warned that the joint should be coated with the flux both on the top and underneath; if this is done thoroughly, the melted flange metal will penetrate completely into the joint.

The flame should be neutral or at most very slightly reducing,(103,191,192) because if the flame is strongly reducing, carbon is absorbed by the weld and the corrosion resistance is materially decreased. Wills and Findley(250) advised preheating the work before welding because of the lower heat conductivity; the welding should be done as rapidly as possible. Puddling should be avoided because this will invariably produce a weld containing excessive oxide inclusions. Lichtenwalter(502) recommended keeping the rod out of the welding cone; when metal must be added, the rod is brought into the reducing-flame envelope but not into the cone.

Compared with the parent metal, the strength of gas-welded joints of low-carbon 18-8 is slightly lowered and the elongation is reduced to approximately one-third. Quenching in water from a high temperature improves both corrosion resistance and mechanical properties and prevents carbide precipitation and intergranular corrosion. According to Hoffmann,(89) the reduction of strength and elongation is greater by oxyacetylene than by arc welding. The filler metal used by Hoffmann was of the same composition as the steel welded, and the specimens were oil quenched from 1200°C. (2190°F.) after welding. Fry(178) claimed that the addition of 3 per cent silicon to 18-8 greatly improves the facility with which it is gas welded.

The low-carbon austenitic steels can be cut with the oxy-acetylene torch provided special technique is employed. In any cutting operation it is essential that the oxides formed flow away from the cut surface so as to expose unoxidized metal. Owing to the refractory nature of the chromium oxide, this does not happen when an oxygen jet is impinged on the surface of these stainless steels. One expedient is the use of the zigzag technique commonly employed in the cutting of cast iron. This puts the cutting jet into contact with unoxidized metal continuously by simply moving it from the initial line of cut. The other method, which gives a more satisfactory cut but which is more limited in its application, involves the use of a carbon-steel cover plate. The oxygen stream acts first on the cover plate and then on the stainless steel immediately under it. The oxide formed by the cover plate washes down over the cut surface of the stainless steel, fluxes the refractory chromium oxide, and permits it to flow off. Thus, a fresh surface is presented for the progressing oxygen jet. Obviously this method is only suitable where a cover plate is mechanically practical.

160. Arc Welding.—The austenitic chromium-nickel steels are readily welded by the metallic-arc process if the necessary precautions are observed. These have been discussed by Bibber,(352) Thomas,(165) Tangerman,(164) and Spraragen.(129) The best results are obtained with direct current and reversed polarity; in other words, the work should be negative and the rod positive. The current used should be as low as possible but high enough to produce thorough fusion, and the arc should be short to minimize oxidation of the filler metal. Owing to the relatively high electric resistivity of stainless steels, the arc voltage is usually somewhat higher than that used for welding plain carbon steel. Puddling is avoided. In welding sections that require a multiple bead, care is taken to remove the oxide formed on the first bead before the second one is laid.

According to Lichtenwalter,(502) it is advisable in design to place the welded seam where it will be stressed the least. Material as light as 22 gage can be welded if the proper fixtures are used. Thick sections need no fixtures. Light gages (up to No. 14) are welded in one pass, heavier ones (14 to 10 gage) are welded in two passes, one on each side of the joint. Plates ¼ to ½ in. thick should be scarfed, and up to five or six passes should be used.

In the welding of these steels it is common to use rods of analysis similar to that of the parent metal, with a few important modifications. In the deposition by means of a covered electrode, there is a small but definite loss of chromium, silicon, and manganese; therefore, the chromium in the rod is usually 1 or 2 per cent higher than in the parent metal; the silicon is raised to between 0.5 and 1 per cent; and the manganese is moderately increased, generally to 1 per cent or more. The increase of these elements is sometimes obtained by incorporation of powdered metallic materials in the coating. Silicon and manganese are particularly useful in this connection in that they oxidize and flux to protect the chromium in the rod during the welding. While in gas welding the use of a suitable flux makes the ratio of manganese and silicon a matter of little moment, in coated electrodes it is important that the composition of the slag be adjusted to give a slag covering of suitable viscosity. Fluorides are frequently used for this purpose, although they are generally considered objectionable because of fumes. As there are a great many types of coatings and as almost nothing is published on the subject of coating composition, no precise rules for ratios of various elements will be given. The viscosity of the slag covering depends on the coating proper and the oxidation products. The combination of these must provide a suitable slag cover. The covering material itself must also have such characteristics that it melts at the proper rate compared with the steel in the rod. This requirement is common to stainless-steel and ordinary carbon-steel coated electrodes.

Although the deposited metal is not normally subjected to the heating effect of welding in the same manner as the base product, with circumferential welds, completed T-welds, or joints with crossed welds the initially deposited weld metal is exposed to the heating effect of the final operation and must be considered in the same manner as the base metal. For this reason it is common to use welding rods that contain a strong carbide-forming element. The reasons for the use of such elements in the welding rod are the same as for using them in the base metal; they are discussed in detail elsewhere (see page 429).

Recently there has been a tendency in Germany to use rods of low-carbon austenitic steels for the electric welding of carbon and low-alloy steels. A typical analysis of such a rod, given by Kautz,(377) is 0.09 per cent carbon, 25 per cent chromium, 20 per cent nickel, and 1.3 per cent manganese.

161. Resistance Welding.—Austenitic chromium-nickel steels are suitable for resistance welding because of their uniform surface finish and their high electric resistivity.(215,277,279,322,468,476) Because of practical interest, such welds have been widely discussed: assembly and preparation of material by Phillips(289) and De Ganahl(218); technique by Hensel,(454) Alexander,(252) Ruppin,(399) and Giroux(270); and theory by Boutté(215) and Kisslyuk.(461) In addition, Geschelin(222) has outlined the methods of testing of spot welds, Whitmer(249) the essential procedure for spot welding sheets of austenitic chromium-nickel steel, and De Ganahl(218) the use of this method by the aircraft industry.

In brief, successful spot welding—a process to which 18-8 is especially adaptable because of its relatively high electric resistivity and low thermal conductivity—demands rigid control of current, pressure, and time. Studies of these factors were reported by Hess and Ringer,(495) Gillette,(422) Ross,(398) Ragsdale,(290) and Arrowsmith in discussion of a paper by Pfeil and Jones,(288) among others. To secure adequate fusion followed by immediate high-speed quenching (by the surrounding metal), heavy currents are applied for brief durations; this means only a few cycles of alternating current, or even fractional cycles.

The resistance method is also practicable for flash welding if certain precautions are observed.(479) Butt welding has been used(255) for joining a valve head of heat-resistant austenitic steel to a stem of wear-resistant low-alloy steel (for example, SAE 3140). Baumgärtel and Heinecke(260) recommended that in making such welds the sections welded be of different lengths to compensate for the difference in electric resistivity. The welds are improved by forging. Satisfactory valves have also been made by welding an austenitic chromium-nickel or chromium-nickel-tungsten steel, for the head, to a cutlery-steel stem.

D. AUTHORS' SUMMARY

1. The melting practice for austenitic chromium-nickel steels is not essentially different from that used for plain low-carbon high-chromium steels. Nickel may be charged, as metallic nickel—or as scrap containing nickel—with the rest of the scrap, or it may be added at any time during the heat. It is not oxidized from the melt and, even though present in large amounts, it plays no important part in controlling the carbon percentage. Low-carbon austenitic chromium-nickel steel scrap is melted in arc or induction furnaces without excessive carbon pickup.

2. Appreciable tonnages of high chromium-nickel steels are poured into castings. Owing to foundry difficulties and the close temperature control necessary in pouring the 18-8 grade, there has been a tendency in the United States to use a steel containing 24 per cent chromium and 12 per cent nickel, or 25 per cent chromium and 20 per cent nickel, both with carbon up to about 0.20 per cent. Such steels have excellent corrosion resistance to certain media. They are usually melted in small acid-lined arc furnaces. The castings are toughened by air or water quenching from 1000 to 1100°C. (1830 to 2010°F.) and are pickled or sand blasted before use.

3. Austenitic chromium-nickel steels are readily hot rolled, but, owing to the strength of the austenite in these steels at elevated temperatures, more power is required than for low-alloy steels or plain high-chromium steels. Accurate temperature control in rolling is essential to avoid corner tears and surface checks. The initial rolling temperature for heavy sections is about 1200°C. (2190°F.); hot working ceases before the metal cools much below 900°C. (1650°F.). Seamless tubes are pierced from billets in regular production, but extra power is needed. Approximately the same initial temperature is used in piercing as in hot rolling, but the final piercing temperature is somewhat higher than the final hot-rolling temperature. Tubes are descaled by pickling, inspected, and finally passivated in a hot 20 per cent nitric acid solution. Sand blasting is not uncommon and permits ready inspection prior to further hot or cold working.

4. Austenitic chromium-nickel steels are readily cold rolled on four-high mills, and reductions up to 30 per cent are usual between softening treatments. Annealing consists of heating at

1000 to 1100°C. (1830 to 2010°F.) followed by rapid cooling. Much of the austenitic steel used in industry is polished after final reduction. This is done both wet and dry with grit or powder containing no iron; elimination of non-metallic particles after grinding and polishing is essential. Chromium or aluminum oxide is used as the final polishing or buffing medium.

5 Ease of fabrication is one of the outstanding properties of austenitic chromium-nickel steels; this is particularly true of the 18-8 variety containing 0.10 per cent carbon or less. The practice in shearing and punching differs from that used for ordinary steel only in that sharper cutting edges and smaller clearances are necessary. The material responds readily to deep stamping for which a Rockwell *B* hardness of 85 or less is specified. The deformability of the material is directly related to the continuous stress-strain curve and the high elongation of low-carbon austenite. Machining at current production rates presents some difficulties in that the work-hardening effect of the tool changes the character of the metal immediately under the cut. For this reason, continuous cutting with keen-edged tools ground slightly flatter than usual has been generally adopted. Special grades of 18-8 containing sulphur or selenium permit free machining; these are discussed in Chapter XIII.

6. All forms of joining, except hammer welding and brazing, may be used for the low-carbon high chromium-nickel steels. These materials can be riveted, but the rivets should be driven very hot to ensure a tight joint and unimpaired corrosion resistance. In soldering, a special flux which will dissolve chromium oxide is necessary, and all surplus flux must be removed to prevent corrosion.

7. Gas or electric welding may be used if precautions are taken to prevent warping, which may result from the low heat conductivity and the high coefficient of expansion of these steels. Oxyacetylene welding is widely employed for thin sheet and electric welding for material ⅛ in. or more in thickness. In gas welding, a neutral flame should be used, and a special flux is necessary to get rid of the refractory chromium oxide. Quenching the welded section in water from a high temperature improves the mechanical properties and prevents intergranular corrosion. A special technique is necessary to cut these steels with the oxyacetylene torch.

8. Reversed polarity and a coated welding rod of the same composition as the parent metal are used in arc welding. Rods containing a strong carbide-forming element, such as columbium, are commonly employed to stabilize the weld. In both gas and arc welding, there is some loss of ductility and corrosion resistance in the metal adjacent to the weld. This is discussed in Chapter XIII.

9. Resistance welding, particularly of the high-speed spot- or seam-welding type, is especially suitable for the low-carbon austenitic steels, owing to their high electric resistance and their uniform surface. In this type of welding, the heat effect in the parent metal near the weld is of minor importance. It is important, however, to regulate the speed of welding and the current and pressure used.

CHAPTER XI

PROPERTIES OF AUSTENITIC CHROMIUM-NICKEL STEELS

Static Properties at Normal Temperatures—Dynamic Properties at Normal Temperatures—Cast and Welded Austenitic Nickel-chromium Steels—Miscellaneous Physical Properties—Effect of Temperature—Authors' Summary

Several years before Maurer, Strauss, and Hatfield began the work which led to the development of the low-carbon 18 per cent chromium, 8 per cent nickel steels, Guillet(3) published the results of his investigations on "quaternary steels." Included in these were materials containing 20 per cent chromium, 5 and 12 per cent nickel, and 0.2 and 0.8 per cent carbon. Only one of the ingots could be forged; this material, containing 0.2 per cent carbon, 20 per cent chromium, and 12 per cent nickel, had a tensile strength, after water quenching from 860°C (1580°F.), of 129,000 lb. per sq. in., a yield strength of 84,000 lb. per sq. in., an elongation of 24 per cent, and a reduction of area of 48 per cent. Guillet's work aroused very little interest and probably had no influence on the development of the austenitic stainless steels.

It is well known that the low-carbon high chromium-nickel steels are not hardened by quenching. They are softest and most ductile after rapid cooling from 1000 to 1200°C. (1830 to 2190°F.) and are hardened appreciably only by cold work. The high-temperature quench to ensure that the steels would be entirely austenitic at room temperature was first described by Strauss and Maurer;(23) these investigators also recognized the effect of carbon on the retention of austenite at room temperature. Bain and Griffiths(80) subsequently pointed out that increasing the nickel content in the low-carbon materials promotes austenite formation and retention. Pilling(155) confirmed the strong influence of nickel on the stability of the austenite; he recommended that for the most stable structure, the nickel should be increased from 8 to 14 per cent. A typical structure of wrought 18-8 steel containing 0.06 per cent carbon, treated by rapid cooling from 1075 to 1100°C. (1965 to 2010°F.), is shown in Fig. 94.

A. STATIC PROPERTIES AT NORMAL TEMPERATURES

As typical austenitic materials, the steels containing less than about 0.1 per cent carbon, 16 to 20 per cent chromium, and 7 to 10 per cent nickel have, when properly heat treated, a tensile strength of 75,000 to 100,000 lb. per sq. in., a yield ratio of 0.5 or less, a low proportional limit, and very high ductility as measured by elongation and reduction of area and by resistance to single-blow impact. Increasing the carbon content increases strength and hardness. The low-carbon 18-8 material hardens rapidly by cold work, and tensile-strength values as high as 350,000 lb. per sq. in. are attained in wire of small cross-section.

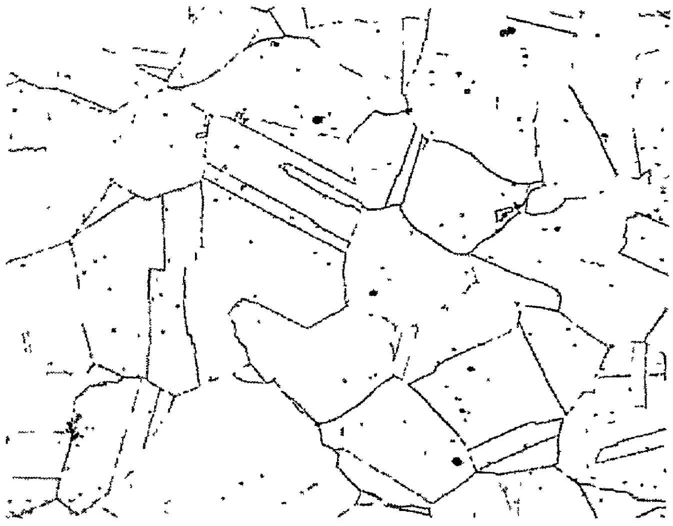

FIG 94.—Typical structure of wrought material containing 0 06 per cent carbon, 18 50 per cent chromium, and 9.5 per cent nickel.

162. Properties of Hot- and Cold-rolled Materials.—The mechanical properties of hot-rolled 18-8 depend upon composition and rolling practice. In general, they fall within the ranges given in Table 78, adapted from a large amount of data for commercial materials collected by Strauss.$^{(162)}$ Somewhat higher strength and lower elongation are frequently obtained, as is evidenced by the following properties averaged from data reported by Newell(194) and Sergeson(126) for rolled 18-8 containing 0.06 to 0.08 per cent carbon:

Tensile strength, lb. per sq in.	107,000
Yield strength, lb per sq in	53,200
Elongation in 2 in., per cent	48.8
Reduction of area, per cent	68.0
Brinell hardness	173
Charpy impact, ft-lb.	101

An elongation of 43 per cent in 2 in., together with a Brinell hardness of 229, was reported for low-carbon material by Scharschu.(402)

TABLE 78.—AVERAGE PROPERTIES OF HOT-ROLLED 18-8*

Property	18-8 containing	
	0.07 per cent carbon	0.16 per cent carbon
Tensile strength, lb. per sq. in.	80,000 to 100,000	80,000 to 110,000
Yield strength, lb. per sq. in.	35,000 to 50,000	35,000 to 60,000
Elongation in 2 in., per cent	50 to 65	45 to 60
Reduction of area, per cent	65 to 75	55 to 70
Brinell hardness	135 to 150	140 to 170
Charpy impact, ft-lb.	90 to 110	90 to 100

* Strauss (162)

Although it is usual to heat treat these steels for optimum ductility, useful properties may be produced by accurate control of the hot-rolling operation. One well-known specification* calls for tensile properties of rounds—too large to be produced by cold rolling—which are well in excess of those resulting from heat treatment, *viz.*, 45,000 lb. per sq. in. proof stress (0.001 in. per in. permanent deformation), 95,000 lb. per sq. in. tensile strength, 25 per cent elongation, 40 per cent reduction of area, 248 Brinell hardness, and 180 deg. cold bend, for specimens from 3-in. rounds. Potts† described the manufacture of steel (containing 0.08 per cent carbon, 0.38 per cent silicon, 0.27 per cent manganese, 19.86 per cent chromium, and 10.61 per cent nickel) by "controlled final hot working at rather low temperatures." In the hot-rolled condition, a 3-in. bar of this material showed 53,300 lb. per sq. in. proof stress, 97,100 lb. per sq. in. tensile strength, 61 per cent elongation, 72.5 per cent reduction of area, and a hardness of 200 Brinell. Potts emphasized the fact that "such material will pass the usual salt-spray and carbide-precipitation tests."

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* U. S. Navy Dept. 46 S 18b, June 1, 1937

† A. D. Potts, private communication.

The effect of cold rolling, as determined by Scharschu,(402) on a steel containing 0.11 per cent carbon, 18.47 per cent chromium, and 8.20 per cent nickel is shown in Table 79.

TABLE 79.—EFFECT OF COLD ROLLING ON THE TENSILE PROPERTIES AND HARDNESS OF LOW-CARBON 18-8*

Reduction by cold rolling, per cent	Tensile strength, lb. per sq. in.	Elongation in 2 in., per cent	Brinell hardness
0	95,000	65	175
20	155,000	25	285
30	172,000	16	310
40	192,000	12	330
55	220,000	8	340

* Scharschu (402)

Comparable data on cold-rolled bars of steel containing 0.07 per cent carbon, 17.98 per cent chromium, and 8.46 per cent nickel, reported by Sergeson(126) and reproduced in Table 80, check Scharschu's data fairly well except for hardness. That the same amount of cold rolling (15 per cent reduction in cross-section of bars approximately 1 in. in diameter) has a different work-hardening effect on 18-8 than on carbon steel is illustrated by the subjoined tabulation in which Sergeson's results are juxtaposed to data obtained by Armour(346) on unalloyed low-carbon steel:

Property	Percentage increase or decrease by cold working, in	
	18-8	Low-carbon steel
Tensile strength, lb. per sq. in.	+37	+36
Yield strength, lb. per sq. in.	+117	+102
Elongation in 2 in., per cent	−38	−58
Reduction of area, per cent	−13	−15
Brinell hardness	+60	+36

TABLE 80.—EFFECT OF COLD ROLLING ON THE MECHANICAL PROPERTIES OF 18-8*

Size, in.	Total reduction by cold rolling, per cent	Tensile strength, lb./sq in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
1.0	0	104,200	54,200	48.0	70 3	170	119
0.925	14 5	142,700	117,800	29.8	61.0	286	88
0.875	23.4	162,500	133,800	21.5	59.1	375	52
0.815	33 6	195,500	166,000	13.0	50 6	418	26
0 750	43 7	227,600	200,500	11.0	44.4	444	17

* Sergeson.(126)

163. Effect of Heat Treatment.—It was mentioned before that the only heat treatment given to low-carbon 18-8 consists of heating to the temperature range between 1000 and 1200°C. (1830 and 2190°F.), followed by cooling rapidly enough—in air, oil, or water, depending upon the size of the section—to retain the carbide in solution and produce an entirely austenitic structure, which has maximum softness and ductility. This treatment is often called "annealing." Because annealing in its usual sense predicates slow cooling and is so defined in the "Metals Handbook,"* the use of the term "annealing" in this sense is avoided in this monograph.

A number of investigators have shown that increasing the temperature of treatment decreases strength and increases ductility. As this has been summarized by Aborn and Bain,(167) it will be sufficient to cite the data reported by Newell,(193) Pilling,(155) Everhart,(221) and Scharschu(402) as typical of the effect of increasing quenching temperature. This was done in Table 81, which indicates that the best quenching temperature for alloys containing less than 0.10 per cent carbon is between 1000 and 1100°C. (1830 and 2010°F.).

Of the many published data on the effect of variation in heat treatment on the properties of 18-8, those of Sergeson(126) may be used to illustrate that variation of tempering temperature has little influence. Test bars of 18-8 containing 0.07 per cent carbon were quenched in oil from 965°C. (1775°F.) and tempered

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* American Society for Metals, Cleveland, 1939, p. 3.

TABLE 81.—EFFECT OF QUENCHING TEMPERATURE ON THE STATIC PROPERTIES OF LOW-CARBON 18-8

Investigator	Composition, per cent					Quenching temperature		Tensile strength, lb./sq in.	Yield strength, lb /sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	C	Mn	Si	Cr	Ni	°C.	°F.						
Newell(193)	0.05	...	....	18.0	8.0	Rolled		106,700	46,600	52	71	170	84
						980	1800	102,100	36,600	54	74	156	85
						1095	2000	101,200	34,000	55	71	143	91
						1150	2100	100,900	33,600	55	71	137	81
						1205	2200	99,400	33,500	57	71	137	96
						1315	2400	95,800	30,000	53	71	131	102
Pilling(155)	0.06	0.23	0.20	17.87	9.79	600	1110	96,300	43,000	54	69	..	116
						800	1470	95,900	46,400	52	70	..	119
						1000	1830	89,700	43,000	58	76	..	119
						1100	2010	84,800	38,000	64	77	..	119
						1200	2190	83,000	37,800	67	78	.	116
Everhart(221)	0.07	.	0.54	16.98	8.93	1010	1850	94,000	28,000	62	75		
						1065	1950	95,000	29,500	60	72		
						1120	2050	96,000	30,000	58	71		
						1175	2150	89,500	27,000	62	68		
						1260	2300	84,000	25,500	66	72		
Scharschu(402)	<0.10	.	....	18.0	8.0	Rolled		110,900	74,000*	43	66	226	109
						870	1600	105,400	56,400*	42	56	217	111
						925	1700	107,100	54,400*	48	56	217	112
						980	1800	106,800	54,900*	43	63	207	112
						1040	1900	93,600	30,600*	58	68	165	112
						1095	2000	90,400	28,500*	61	68	163	112

* Reported as proportional limit.

at temperatures ranging from 260 to 705°C. (500 to 1300°F.). Tensile-strength values varied from 100,000 to 108,000 lb. per sq. in., yield strength from 42,300 to 44,900, elongation in 2 in. from 47.0 to 54.5 per cent, and reduction of area from 60 to 69 per cent. There was some indication that Brinell hardness was higher for bars tempered at the lower temperatures than for those tempered at the higher temperatures of the range.

164. Effect of Time at Elevated Temperature.—Because the low-carbon 18-8 materials are used in applications involving long-continued heating, it is important to know the effect of such treatment on the properties. Data reported by Newell,(193) Strauss, Schottky, and Hinnüber,(161) Scharschu,(402) the Babcock and Wilcox Tube Company,(169) and the Allegheny Steel Company* indicate that, in general, heating for several thousand hours has little effect on the strength; however, it may affect deleteriously the ductility and toughness as represented by elongation, reduction of area, and impact; the decrease of these values depends largely upon the carbon content. Newell,(193) for example, found that, if the alloy contained less than 0 10 per cent carbon, the elongation, reduction of area, and impact resistance of oil-still tubes, although somewhat impaired, were high after 13,500 hr. at 495°C. (920°F.). Data reported by Scharschu(402) indicate that after a treatment at 535°C. (1000°F.) for almost 2000 hr., there was little loss in impact resistance even if the carbon was 0.17 per cent. Treatment at 650, 790, and 850°C. (1200, 1450, and 1560°F.), however, yielded entirely different results. Steels with 0.07 and 0.09 per cent carbon showed little loss in impact strength upon long exposure to these temperatures; 0.11 and 0.17 per cent carbon steels, on the contrary, suffered a loss of at least half of the impact strength. In Charpy notched-bar impact tests conducted by Han,(225) steels containing 0.06 and 0.085 per cent carbon embrittled appreciably when held for 1000 hr. between 550 and 870°C. (1020 and 1600°F.).

The cause for this embrittlement, carbide precipitation at the grain boundaries, is discussed in detail on page 272. Some of the data from the aforementioned investigations are collected in Tables 82 and 83.

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* Private communication to Aborn and Bain.(167)

TABLE 82.—EFFECT OF TIME OF HEATING ON MECHANICAL PROPERTIES

Investigator	Composition, per cent			Heating temperature		Time, hr.	Tensile strength, lb./sq in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Impact, ft-lb.		Brinell hardness
	C	Cr	Ni	°C.	°F.						Izod	Charpy	
Newell(193)	0.05	18.0	8.0	495	920	10,200	96,200	38,900	41	32	.	57	152
	0.06	18.0	8.0	495	920	13,500	85,200	38,500	44	42	..	73	152
Strauss, Schottky, and Hinnüber(161)	0.12	18.0	8.0	600	1110	0	92,600	....	60	..	..	24.2*	
				600	1110	1	92,800	....	62	.	..	22.0*	
				600	1110	50	94,400	..	60		.	20.9*	
				600	1110	300	94,800	..	56		..	20.8*	
				700	1290	0	92,600	....	60		.	24.2*	
				700	1290	1	93,600	...	61	..	.	22.7*	
				700	1290	50	97,600	...	57	..	..	19.2*	
				700	1290	300	103,500	...	47	.	.	12.3*	
				800	1470	0	92,600	...	60		..	24.2*	
				800	1470	1	91,000	...	62	.	.	21.7*	
				800	1470	50	98,200	.	49			11.7*	
				800	1470	300	98,600	.	50		.	3.7*	
Scharschu(402)	0.07	17.80	8.68	650	1200	0	87,700	19,000	65				
				650	1200	527	91,700	17,500	55				
				650	1200	3,068	94,900		49				
	0.11	18.13	7.81	650	1200	0	91,300	25,000	57				
				650	1200	527	99,900	26,500	43				
				650	1200	3,068	113,200	22,000	41				
	0.17	18.65	7.68	650	1200	0	96,000	32,600	65				
				650	1200	527	117,100	28,600	43				
				650	1200	3,068	117,800	23,700	38				

* M-kg per sq. cm.

TABLE 82.—EFFECT OF TIME OF HEATING ON MECHANICAL PROPERTIES.—(*Continued*)

Investigator	Composition, per cent			Heating temperature		Time, hr.	Tensile strength, lb./sq. in.	Yield strength, lb./sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Impact, ft-lb.		Brinell hardness
	C	Cr	Ni	°C.	°F.						Izod	Charpy	
Allegheny Steel Company†	0.07	17.8	8.7	650	1200	509	94,500	36,500	53	66			
				770	1420	2,387	93,500	34,500	46	64			
				800	1470	500	91,000	32,500	55	66			
				540	1000	1	. . .	.....	..	..	112	....	131
				540	1000	1,000	. .	. ..	.	.	107	.. .	121
				650	1200	1	......	....	.	..	113	. .	119
				650	1200	3,068	. ... .	. .. .	..		105	....	131
	0.11	18.0	8.0	540	1000	1	..... .	. . .	.	..	112	. .	131
				540	1000	1,971	. ...	....	.	.	106	. ..	143
				650	1200	1	.. ...	.. .		..	109	.	135
				650	1200	3,068	. ..	.. ..	.	.	30	. ..	163
				845	1550	1	.. .	. ..	..	..	112	.	137
				845	1550	3,316	.	. .	..	.	63	. .	126
	0.17	18.0	8.0	650	1200	1	... ..	. ...	..	..	114	. .	136
				650	1200	2,059	....	.. .	.	.	35	. .	190

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† See footnote, p. 308.

165. Effect of Carbon Content and Grain Size.—Carbon has a pronounced effect on the tensile properties of 18-8 steels. Commercial steels, which contain up to about 0.20 per cent carbon, are usually divided into two groups, one with a maximum carbon content of 0.08 per cent, the other with carbon between 0.08 and 0.20 per cent. The effect of increasing carbon is illustrated by Scharschu's data, given in Table 84, which were obtained on hot-rolled 1-in. round bars water quenched from 1150°C.

Table 83—Effect of Long Heating on the Hardness and Impact Resistance of 18-8*

Temperature		Time, hr.	0.07 per cent carbon†		0.11 per cent carbon		0.17 per cent carbon	
°C.	°F.		Izod impact, ft-lb.	Brinell hardness	Izod impact, ft-lb.	Brinell hardness	Izod impact, ft-lb.	Brinell hardness
535	1000	1	112	131	112	131	113	143
		980	112	135	108	149	103	143
		1971	107	121	106	143	107	163
650	1200	1	113	119	109	135	114	136
		2059	104	135	43	168	35	190
		3068	107	131	30	163	35	197
790	1450	1	...	...	113	143	113	162
		1390	96	133	57	164	66	177
		2387	93	126	56	170	63	179

* Scharschu.(402)
† Complete compositions are given in Table 82.

Table 84.—The Effect of Carbon on the Mechanical Properties of 18-8*

Carbon, per cent	Tensile strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
0.065	79,000	19,500	70	72	140
0.11	85,000	25,000	69	76	163
0.15	90,000	28,000	69	73	166
0.17	93,000	30,000	68	75	170

* Scharschu (402)

(2100°F.). It is apparent from these values that the principal effect of carbon is to increase the tensile strength and hardness and, especially, the proportional limit; it has little effect on elongation and reduction of area.

Despite the fact that carbon has apparently little effect on ductility after ordinary heat treatment, there is little doubt that 18-8 material containing 0.09 to 0.20 per cent carbon withstands long-continued heating to high temperatures less well than the lower carbon materials. This is emphasized by Newell(385):

> The impact value of low-carbon 18-8 . . . prior to service is excellent [70 ft-lb. or more in the Charpy test] . . . Continued heating in a cracking coil may reduce this to 35 ft-lb. which is still ample to withstand any shock likely to be met. In higher carbon alloys the original impact value of the alloy may decline on long heating to 25 ft-lb. or even less depending on the temperatures.

If low-carbon 18-8 is heated at too high a temperature or held at a high temperature for too long a time, grain growth occurs. The extent to which this takes place depends on the temperature, period of time at temperature, prior state of the metal, and analysis, particularly the carbon content. The thicker sections, such as plates and rounds, may be held for a longer period than thin-gage sheet and strip. It is common practice to hold the latter for only a few minutes at temperatures between 1000 and 1100°C. (1830 and 2010°F.) because this prevents grain growth and results in a surface that can be descaled easily. The use of higher temperatures results in excessive scaling and poor surface after descaling or necessitates protective atmospheres. Grain growth is an integrated time-temperature effect, and articles that have developed large grains are unsuitable for severe cold work because of the resulting rough surface known as the "orange-peel" effect.

Newell(194) has shown, as is discussed later in this chapter, that the ductility of 18-8 at elevated temperatures is greatly affected by grain size. According to Scharschu,(402) grain size may also affect the ease with which the material undergoes subsequent fabrication. Considerable differences in grain size are, however, not accompanied by great variations in mechanical properties at room temperature. For example, Newell gave the following properties as typical for 18-8 containing 0.056 per cent carbon, treated in such a way that one sample had small grains, whereas in the other one marked grain growth had occurred. The large-grained material has somewhat lower strength and hardness and higher notch toughness, *viz.:*

Property	Small grains	Large grains
Tensile strength, lb. per sq. in	102,100	94,600
Yield strength, lb. per sq. in.	36,600	31,500
Elongation in 2 in, per cent	54.3	58.7
Reduction of area, per cent	73.5	71.4
Brinell hardness	156	137
Charpy impact, ft-lb	85	101.5

166. Static Properties of 18-8 Wire.—As is characteristic of carbon and low-alloy materials, the properties of 18-8 wire depend upon the amount of drawing and upon the size of the wire. According to Wills and Findley,(250) material to be cold drawn into wire should contain 9 to 10 per cent nickel, not more than 0.07 per cent carbon, 0.30 to 0.50 per cent manganese, and 0.20 to 0.40 per cent silicon; these are somewhat closer limits than those specified for material to be hot or cold rolled. The effect of cold drawing an annealed rod from 0.250- to 0.105-in. diameter on the properties is shown in Table 85.

TABLE 85.—EFFECT OF DRAWING ON THE TENSILE PROPERTIES OF 18-8 WIRE CONTAINING 0 07 PER CENT CARBON*

Reduction by drawing, per cent	Tensile strength, lb. per sq in.	Yield strength, lb per sq in.	Brinell hardness
0	88,000	35,000	135
20	120,000	90,000	230
40	160,000	150,000	300
60	210,000	200,000	370
80	255,000	255,000	400
90	260,000	260,000	400

* Wills and Findley.(250)

The increase in the tensile strength of 18-8 by cold drawing as compared with patented 0.54 per cent carbon steel, unpatented 0.9 per cent carbon steel, and Monel metal is shown in Fig. 95.

The austenitic steel hardens more rapidly, but the final strength is only very slightly greater than that of the patented medium-carbon steel. Wills and Findley stated that, although drafts greater than 85 per cent have been made with fine wire (less than 0.030 in. in diameter), the maximum draft which is practicable with the larger sizes is 75 per cent. With drafts of 95 to 97 per cent, the tensile strength of fine 18-8 wire may be as high as 400,000 lb. per sq. in.

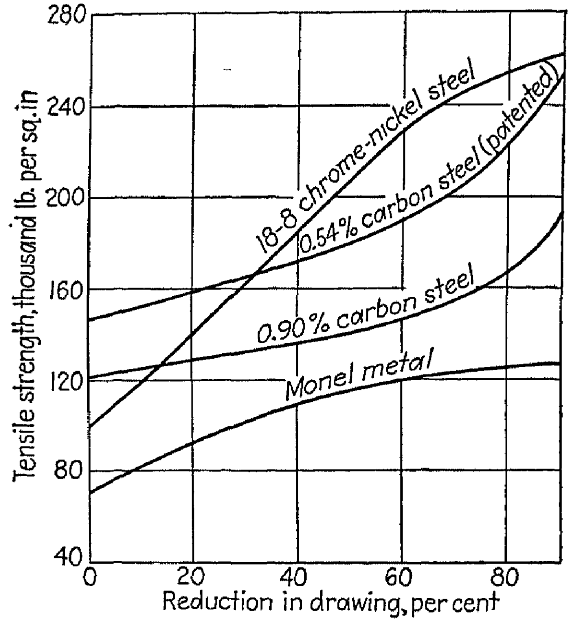

FIG. 95.—Effect of cold drawing on the tensile strength of Monel metal, carbon steel, and 18-8 wire. (*Wills and Findley.*[250])

The decrease of elongation and reduction-of-area values is illustrated by the following:

Reduction in cross-section by drawing, per cent	Decrease of elongation in 8 in.	Decrease of reduction of area
25	From 50 to 30 per cent	
60	From 50 to 1 per cent	From 70 to 55 per cent

The properties of softened wire, *i.e.*, water quenched from about 1095°C. (2000°F.), are practically the same as the properties of softened sheet and strip given in the next section. The effect of softening temperature on the tensile strength and elongation is shown in Fig. 96.

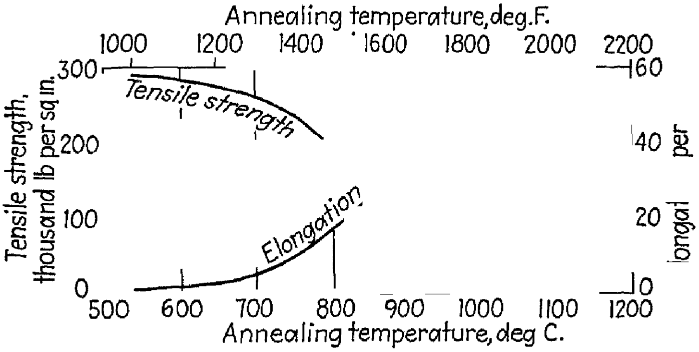

Fig. 3 —Effect of annealing temperature on the tensile properties of cold-drawn 18-8 wire. (*Wills and Findley* (250))

The relation of tensile and yield strengths to size of hard-drawn 18-8 and, for comparison, of low-carbon 16 to 18 per cent chromium iron wire is given in Table 86. For the same sizes, the 18-8 wire is about twice as strong as the low-carbon chromium-iron wire.

Table 86.—Relation of Tensile and Yield Strengths to Size of Hard-drawn 18-8 and Low-carbon 16 to 18 Per Cent Chromium Iron Wire*

Diameter of wire, in.	18-8		Low-carbon 16 to 18 per cent chromium wire	
	Tensile† strength, lb./sq. in	Yield strength, lb./sq. in.	Tensile strength, lb./sq. in	Yield strength, lb /sq. in.
0.004	350,000	335,000	210,000	182,000
0 008	317,000	310,000	177,000	160,000
0 012	300,000	292,000	157,000	137,000
0 016	293,000	280,000	148,000	128,000
0 020	285,000	273,000	138,000	120,000
0.024	277,000	266,000	136,000	120,000
0.028	273,000	263,000	135,000	120,000

* Wills and Findley (413)

† Minimum values

167. Effect of Carbon Content and of Heavy Drafts on the Properties of 18-8 Wire.—In another paper, Wills and Findley(342) reported on the effect of carbon content on mechanical properties. To attain the same high strength value (in rope or spring wire), 18-8 containing 0.17 per cent carbon requires 5 to 7 per cent less drafting than wire containing 0.08 per cent or less carbon. Owing to the fact that for the same tensile strength the higher carbon wire is not drawn so severely, it is less magnetic than the low-carbon material; for certain applications this may be an advantage. These findings are contradicted by the results of Scharschu,(402) who found that for the same reduction by drawing the lower carbon wire had the higher strength, in other words, hardened more rapidly by cold work. The data of Wills and Findley and of Scharschu are summarized in Table 87. Scharschu's wire was drawn from 0.50 to 0.10 in. without annealing. Details concerning the sizes of the wire and of the rod from which it was drawn are not given in Wills and Findley's paper.

TABLE 87.—EFFECT OF DRAWING ON THE TENSILE STRENGTH OF 18-8 WIRE

Reduction by drawing, per cent	Tensile strength, lb. per sq. in.			
	Wills and Findley(342)		Scharschu(402)	
	0.06% carbon	0.17% carbon	0.06% carbon	0 17% carbon
20	145,000	175,000	115,000	120,000
40	195,000	220,000	200,000	190,000
60	230,000	245,000	270,000	250,000
80	255,000	270,000	370,000	320,000

The chief disadvantage of increasing the carbon content is the increased susceptibility to carbide precipitation. Wills and Findley(342) also stated that in making hard-drawn 18-8 wire for rope and springs with a tensile strength of 300,000 lb. per sq in , increasing the nickel to 11 per cent and maintaining the carbon at 0.07 per cent results in a material with excellent torsional properties and with a higher endurance limit than that obtained in wire with higher carbon and 8 per cent nickel.

In an investigation made primarily to determine the effect of a lead coating on the drawing of austenitic chromium-nickel wire, Francis(315) used both light and heavy drafts on material containing 0.16 per cent carbon, 15.7 per cent chromium, and 10.2

per cent nickel. Results are given in Table 88. They indicate that drawing with a reduction of 87.6 per cent (from 0.0733 to 0 0258 in.) in 9 drafts results in slightly higher strength than drawing 87.6 per cent in 6 drafts.

TABLE 88 —EFFECT OF HEAVY AND LIGHT DRAFTS ON THE STATIC PROPERTIES OF 0.16 PER CENT CARBON, 15.7 PER CENT CHROMIUM, 10.2 PER CENT NICKEL STEEL WIRE*

Size of wire, in.	Reduction by drawing		Tensile strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
	Number of passes	Total reduction, per cent			
0 0733	0	0	96,100	80	71 8
0 0685	1	12 5	111,300	50	70 6
0 0421	4	67 0	218,400	8	53 0
0.0359	2	76.0	244,200	5	57 5
0.0298	1	83.5	251,100	5	50 0
0 0258	1	87.6	265,400	5	43 0
0 0685	1	12.5	111,300	50	70.6
0 0421	2	67.0	209,500	8	59 9
0 0359	1	76.0	235,400	7	52.4
0.0298	1	83 5	244,200	6	50.7
0.0258	1	87 6	262,100	5	43 5

* Francis (315)

168. Static Properties of 18-8 Sheet and Strip.—Typical static properties of 0.08 per cent carbon, 18.45 per cent chromium, 8.96 per cent nickel plate and sheet, after air cooling from 1100°C. (2010°F.), are given in Table 89. The variations in values are not significant and are not characteristic of size.

TABLE 89 —STATIC PROPERTIES OF 18-8 SHEET AND STRIP, AIR COOLED FROM 1100°C. (2010°F.)

Property	½-in. plate	¼-in. plate	⅛-in. sheet
Tensile strength, lb. per sq. in	87,500	89,000	85,600
Yield strength, lb. per sq. in.	39,000	38,600	37,000
Elongation in 2 in., per cent	59	61	60
Brinell hardness (3000-kg load)	143		
Rockwell *B* hardness	.	80	80

Carbon increases the strength and reduces the ductility of softened sheet by about the same amounts as in hot-rolled and softened bars. This was shown by Johnson and Sergeson(373) as follows:

Carbon, per cent	Tensile strength, lb. per sq. in.	Yield strength, lb. per sq. in.	Elongation, per cent, in	
			2 in.	8 in.
0.07	86,400	30,000	65	56
0 16	93,300	46,600	57	50

For deep drawing, Hostettler(369) recommended that 20-gage material have the following properties: tensile strength, 90,000 lb. per sq. in.; yield strength, 40,000 lb. per sq. in.; elongation in 8 in., 45 per cent; Olsen cup test, 0.450 to 0.550; and Rockwell *B* hardness, 80.

Data reported by Johnson and Sergeson(373) indicate that cold-rolled 18-8 strip is stronger and more ductile than low-carbon 14 or 18 per cent chromium iron strip similarly treated. This is shown by Table 90. The maximum reduction by cold rolling used was about 35 per cent. The effect of further reductions was shown recently by Krivobok,(501) for material containing 0.08 per cent carbon, 18.10 per cent chromium, and 9.08 per cent nickel, to be as follows:

Reduction by cold rolling, per cent	Tensile strength, lb. per sq. in.	Elongation in 2 in., per cent
Annealed	94,400	70
20	127,000	30
30	143,800	16
40	164,900	9
50	175,500	5
60	194,500	3

In another paper Krivobok and associates(464) pointed out that the strength, ductility, and "workability" of the 18-8 steel strip change sharply with variations in composition and are influenced by the tendency of the austenite to change to ferrite during cold working. His results indicated that the 18-8 steels containing from 0.10 to 0.15 per cent carbon and from 7 to 8 per cent nickel had optimum properties for practical applications after cold rolling to tensile strengths in the neighborhood of 200,000 lb. per sq in. However, Monypenny* pointed out that there are other considerations, such as need for maximum 0.1 per cent proof stress together with minimum tensile strength, for ease in fabrication and that the 8 to 9 per cent nickel alloys meet this requirement better than those with 7 to 8 per cent nickel.

TABLE 90.—PROPERTIES OF COLD-ROLLED STAINLESS-STEEL STRIP*

Condition	Size, in.	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation, per cent, in		Rockwell hardness	
				2 in.		*B*	
	0.09 per cent carbon, 14 per cent chromium						
Annealed	0.127	106,000	79,700	23.0	12.5	93	
First pass..	0.111	123,600	116,300	9.5	2.5	.	18
Second pass.	0.094	131,900	124,800	5.5	1.0	.	21
Third pass..	0.084	136,700	128,600	5.0	1.0	.	22
	0.09 per cent carbon, 18 per cent chromium						
Annealed	0.122	88,500	60,100	23.0	14.5	90	
First pass..	0.109	101,600	71,300	10.0	3.5	..	13
Second pass.	0.094	110,600	107,100	7.0	2.0	.	18
Third pass..	0.084	117,400	112,500	4.5	1.7	..	19
	0.08 per cent carbon, 18 per cent chromium, 8 per cent nickel						
Annealed	0.129	91,800	43,200	62.5	47.5	84	
First pass..	0.111	120,000	98,700	32.0	23.5		24
Second pass.	0.097	141,300	119,200	20.5	9.0	..	31
Third pass	0.084	167,200	109,300	13.0	5.0	..	34

* Johnson and Sergeson.(373)

169. Effect of Higher Nickel Percentages.—Increasing the nickel of low-carbon 18-8 increases the stability of the austenite. As mentioned on a previous page, this has been demonstrated by Bain and Griffiths(80) and by Pilling.(155) The latter determined the effect of up to 14 per cent nickel on the properties of

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* J. H. G. Monypenny, private communication.

18-8. The result was a marked softening. The decrease in strength was accompanied by an increase in elongation, especially after quenching from 1000°C. (1830°F.). The most important effect, however, is the lowered effectiveness of carbon in increasing the strength. This is shown by Fig. 97. Another

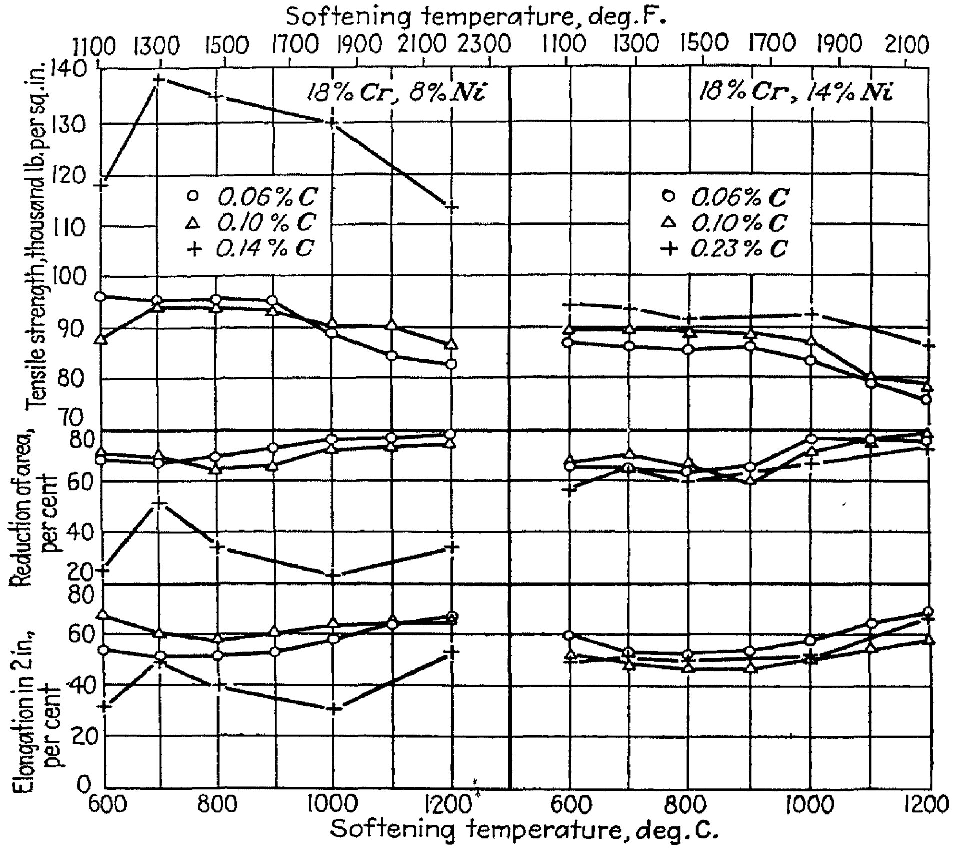

FIG. 97.—Effect of carbon on the tensile properties of 18 per cent chromium steels containing 8 and 14 per cent nickel, softened at various temperatures. (*Pilling*.(155))

effect noted by Pilling was that the 14 per cent nickel alloys harden less rapidly by cold work than the 18-8 material. This is shown by the hardness values in Table 91.

The effect of increasing the nickel from 7 to 9 per cent was determined by Krivobok and associates.(464) Some of their data are given in Table 92. These show that increasing the nickel reduces the tensile strength and increases the elongation of the low-carbon alloys considerably, not only in the softened state, but also after cold rolling with a reduction of 50 per cent. The effect of nickel on the steels containing about 0.15 per cent carbon is not nearly so pronounced, especially in respect to elongation.

TABLE 91.—EFFECT OF COLD ROLLING WITH 20 PER CENT REDUCTION ON THE HARDNESS OF AUSTENITIC CHROMIUM-NICKEL STEEL*

Composition, per cent			Brinell hardness after water quenching from 1200°C. (2190°F.)	
C	Cr	Ni	Before cold rolling	*After cold rolling*
0.06	18	8	130	148
0 10	18	8	123	187
0 14	18	8	128	243
0 06	18	14	109	141
0 10	18	14	109	141
0.23	18	14	116	140

* Pilling (155)

170. Effect of Higher Chromium and Nickel Percentages.—Austenitic steels containing greater percentages of chromium and nickel are more suitable than the 18-8 group for high-temperature service because of their increased resistance to corrosion and oxidation and their improved high-temperature strength These steels may be divided into two groups, one of which contains 22 to 25 per cent chromium with 10 to 14 per cent nickel, whereas the other contains 20 to 25 per cent chromium and 20 to 22 per cent nickel. With these higher percentages of chromium and nickel the carbon content may be raised to a maximum of 0.20 to 0.25 per cent for wrought products and to 0.50 per cent for castings without serious effect on corrosion resistance. However, such high carbon has not been accepted universally, and there is still a strong tendency to specify the maximum carbon content at one one-hundredth of the chromium content.

The properties of these steels are similar to those of the 18-8 steels. The data given in Table 93 show the effect of water quenching from different temperatures on the mechanical properties of a typical wrought 24 per cent chromium, 12 per cent nickel steel. They were obtained on hot-rolled bars, held 1 hr. at the respective temperatures; the figures given for the "hot-rolled" condition imply an appreciable amount of work hardening. This may occur in hot rolling small sizes but is not so likely in the case of large bars or forgings. Thus, the values for the hot-rolled material given in the table cannot be considered as representative for these steels and, indeed, mainly

TABLE 92.—EFFECT OF NICKEL ON THE PROPERTIES OF SOFTENED AND COLD-ROLLED HIGH CHROMIUM-NICKEL STEEL STRIP*

Composition, per cent			Softened		Cold rolled 30 per cent		Cold rolled 50 per cent	
C	Cr	Ni	Tensile strength, lb./sq. in.	Elongation in 2 in., per cent	Tensile strength, lb./sq. in.	Elongation in 2 in., per cent	Tensile strength, lb./sq. in.	Elongation in 2 in., per cent
0.053	17.13	7.07	132,000	20	183,000	6	205,000	1.5
0.050	16.83	9.79	86,000	65	129,000	20	160,000	5.5
0.056	18.68	7.33	122,000	41	183,000	8	213,000	1.5
0.051	18.22	9.14	86,000	65	122,000	21	156,000	5.0
0.140	17.26	7.07	128,000	80	206,000	20	255,000	6
0.130	17.08	9.65	94,000	70	140,000	20	175,000	7
0.160	19.68	6.68	102,000	72	156,000	37	194,000	9
0.160	18.88	8.78	98,000	63	142,000	33	176,000	8

* Krivobok *et al.*(464)

TABLE 93.—EFFECT OF HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF STEEL CONTAINING 24 PER CENT CHROMIUM AND 12 PER CENT NICKEL*

Temperature of treatment		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
°C.	°F.					
Hot rolled		130,530	107,300	31	60	262
870	1600	122,880	88,360	32	55	234
925	1700	120,520	89,760	34	57	229
980	1800	109,850	59,940	44	60	187
1040	1900	107,320	56,640	49	62	179
1090	2000	100,250	49,370	58	70	149
1150	2100	95,520	45,750	62	69	143

* Allegheny Ludlum Steel Corporation.(485)

serve to show the possibility of great variation in the hot-rolled product. As in the case of the 18-8 steel, it is not advisable to heat at temperatures in excess of about 1090°C. (2000°F.) because of attendant grain growth.

Wrought low-carbon steels of the group containing 20 to 25 per cent chromium and 20 to 25 per cent nickel develop the mechanical properties shown in the subjoined table. These values were obtained on samples of steel containing 0.14 per cent carbon, 25.06 per cent chromium, and 20.22 per cent nickel, rapidly cooled from 1090°C. (2000°F.):

Tensile strength, lb. per sq. in.	90,500
Yield strength, lb. per sq. in.	50,000
Elongation in 2 in., per cent	47
Reduction of area, per cent	63
Izod impact value, ft-lb	90
Brinell hardness	153

Additional data are given by Monypenny.(191)

B. DYNAMIC PROPERTIES AT NORMAL TEMPERATURES

One of the outstanding characteristics of the wrought low-carbon 18 per cent chromium, 8 per cent nickel steels and of other austenitic steels of this class is great toughness as shown by resistance to notched-bar impact and by relatively low notch sensitivity. The endurance ratio of these steels, when heat treated and not cold worked, is low, usually considerably lower than that of carbon and low-alloy materials. However, owing to their resistance to many forms of corrosion, these steels have a higher corrosion-endurance limit, as determined by the usual tests, than those obtained under comparable conditions for carbon and low-alloy steels.

171. Impact Properties.—The Izod impact resistance of low-carbon 18-8 in the fully softened state is usually between 100 and 120 ft-lb. and is unaffected by heat treatment, provided the treatment does not cause carbide precipitation. Thus, Sergeson(126) found that, after quenching, the Izod value was 119 to 120 ft-lb. regardless of whether the cooling medium was air, oil, or furnace, and that varying the tempering temperature had no effect.

The impact resistance of 18-8 as affected by carbon content and various heat treatments is given in tables and in the text in previous sections of this chapter. These data justify the conclusions that (*a*) the impact value of quenched material is higher than that of rolled steel of the same composition; (*b*) increasing the quenching temperature has little or no effect, provided no appreciable carbide precipitation takes place; (*c*) increasing the carbon content from 0.07 to 0.17 per cent has no effect, also provided that no carbide precipitation takes place; and (*d*) cold working decreases impact resistance. The effect of cold working is shown in Table 80 (page 306); reducing a 1-in. round 43.7 per cent by cold rolling lowers the Izod impact from 119 to 17 ft-lb

It is discussed later that impact is a sensitive test for the detection of carbide precipitation. This is shown by data of Strauss, Schottky, and Hinnüber and of the Allegheny Steel Company, which are quoted in Table 82. Bain, Aborn, and Rutherford(259) also used the Izod test in their study of intergranular corrosion of 18-8. Impact resistance at room temperature was determined on material containing 0.07 and 0.11 per cent carbon after heating to, and holding at, various temperatures for various times. Results are shown in Table 94.

TABLE 94.—EFFECT OF TIME AND TEMPERATURE ON IZOD IMPACT VALUES, DETERMINED AT ROOM TEMPERATURE, OF UNSTABILIZED 18-8*

Temperature		Time of heating, hr.	Izod impact, ft-lb.	
°C.	°F.		0 07 per cent carbon	0.11 per cent carbon
540	1000	1	112	112
540	1000	1971	107	106
650	1200	1	113	109
650	1200	2059	104	43
650	1200	3068	105	30
845	1550	1	112	112
845	1550	2307	94	55

* Bain, Aborn, and Rutherford.(259)

172. Endurance Limit at Normal Temperatures.—Available recent data on the endurance of 18-8 after a variety of treatments are collected in Table 95. They indicate that the endurance ratio of rolled material is about the same as the value (0.50) usually obtained on carbon and low-alloy steels; quenching, however, lowers the ratio considerably. Scharschu's results show that increasing the carbon increases the endurance limit,

TABLE 95.—ENDURANCE LIMIT OF 18-8

Investigator	Composition, per cent				Treatment	Tensile strength lb./sq.	Yield strength lb./sq	Endurance limit, lb./sq.	Endurance ratio
		Mn	Cr	Ni					
Russell and Welcker(199)	0 09	0.39	17 51	9.24	Quenched	88,000		33,000	0 38
	0 12		18 76	8 41	Cold worked	112,000		62,000	0 55
	0 11		18 40	9.63	Cold worked	135,000		74,000	0 54
Haven(228).	0.13	0 35	18.83	8 49	Cold-worked streamline wire	188,000	185,000	27,500*	0.15*
Mailänder(231).	Low				Not given	102,400	54,000	48,400	0 53
Cross(312)	0.067	0 50	18 21	9 56	Rolled	85,000	36,500	40,000	0 47
	0 125	0 47	18 50	9 67	Rolled	91,000	41,000	42,000	0 46
Scharschu(402) .	0 065				Water quenched from 1150°C. (2100°F.)	79,000	19,500	32,000	0 41
	0 11				Same	85,000	25,000	34,000	0 40
	0 15				Same	90,000	28,000	36,500	0 40
	0 17				Same	93,000	30,000	38,000	0 41
Russell and Welcker(438)	0 09	0.39	17 54	9 24	Quenched	88,000		33,000	0 38
					Same; sharp 90-deg. notch			6,000	0 41
Cazaud and Persoz(310,447)	0 17		17.75	8 25	Air cooled from 1100°C. (2010°F.)	94,600	33,400	32,700	0 35
Oberg and Johnson(470). .	0 06		19.98		Quenched		34,800	36,000	0 43
					Same; 60-deg notch, 0.01-in. radius			43,000	0 52
	0.05		20 09	3 87	Cold drawn	132,500	109,000	0,000	0 53
					Same; notched as above			0,000	0 38
Habart and Caughey(522)	) 07	0.46	18.80	.62	Water quenched. Fine grain	94,400	39,400	39,000	0.39
					Cold worked and recrystallized. Coarse grain	90,900	32,400	34,000	

* Torsion fatigue, specimens not polished.

but the ratio is unchanged. Concerning this lowering by quenching, Scharschu(402) stated:

> For example, material [composition and treatment not given] having a tensile strength of 109,000 lb. per sq. in. . . . [has] a Wohler fatigue

limit of 54,000 lb. per sq. in. [endurance ratio 0.50]. When . . . water quenched from 1150°C. (2100°F.), the tensile strength is reduced to 85,000 lb. per sq. in. and a fatigue limit of only 26,000 lb. per sq. in. [ratio 0.31] is obtained. . . . When annealed [quenched] at 1065 to 1150°C. (1950 to 2100°F.) the endurance limit is only half of the value obtained for the hot-rolled steel.

As is apparent from the results of Russell and Welcker(438) and of Oberg and Johnson(470) (Table 95), cold working increases both the endurance limit and the endurance ratio. Results by Habart and Caughey(522) show that coarse grain is responsible for lowered tensile strength and endurance limit, but the ratio is unchanged.

One of the peculiarities of fully austenitic materials is that, ordinarily, their endurance limit is higher than the yield point Another peculiarity, as pointed out by Russell and Welcker(438) and by Oberg and Johnson,(470) is that notching increases both endurance limit and ratio of the softened alloy. This is presumably caused by the local cold working at the base when the notch is cut. Oberg and Johnson's data also show that notching decreases the endurance limit and ratio if the material is cold worked.

Russell and Welcker(199) found that two factors affect the endurance limit of 18-8 importantly. The first is the elastic hysteresis that occurs in a highly stressed specimen and that may raise the temperature to a red heat and cause failure by bending.

> For stresses slightly above the endurance limit the specimen heated slowly at first, then rapidly to a temperature which caused oxidation. All fractures were irregular and unlike a "characteristic" fatigue failure.

According to Russell and Welcker, the general effect of elastic hysteresis is to lower the endurance limit. Opposed to this is the marked strengthening by stresses just below the endurance limit, which tends to raise the endurance limit. The investigation by Russell and Welcker of the factors which affect the endurance of 18-8 has not received the attention it deserves by later workers in this field.

173. Corrosion Endurance.—The resistance of low-carbon austenitic chromium-nickel steels to simultaneous stress and corrosion depends largely on the corroding medium. It was noted by McAdam,(48) Inglis and Lake,(183) and Gough and Sopwith, (224,271,453) among others, that if the corroding medium

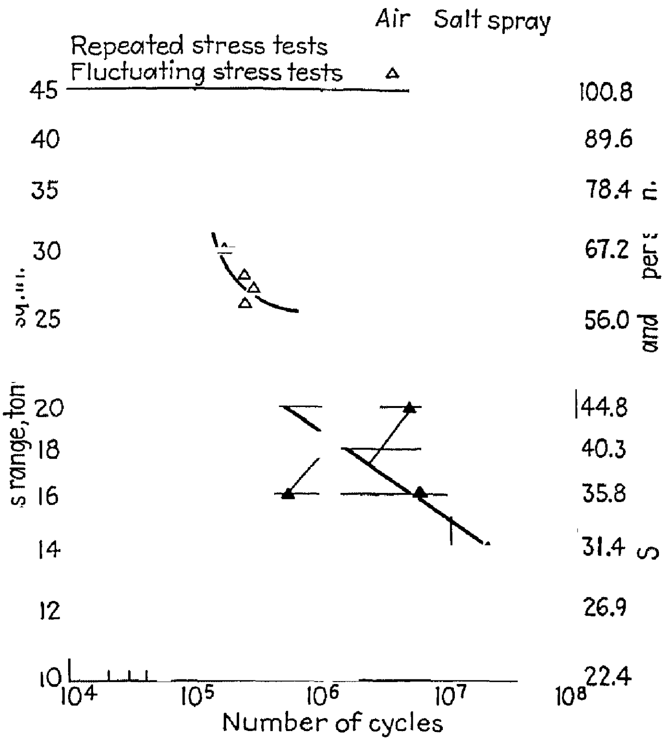

FIG. 98—Endurance tests of 18-8 in air and in salt spray. (*Gough and Sopwith.*[453])

TABLE 96.—CORROSION-ENDURANCE LIMITS OF AUSTENITIC CHROMIUM-NICKEL STEELS*

Property	Steel *A* 0 16% C 17 32% Cr 8 19% Ni	Steel *B* 0 39% C 17.71% Cr 25 27% Ni
Tensile strength, lb. per sq. in ...	125,300	115,200
Endurance limit, in air, lb. per sq. in	50,000	54,000
Endurance ratio..	0 40	0.47
Endurance limit, in fresh water, lb. per sq. in.........	50,000	45,000
Endurance ratio	0 40	0.39
Endurance limit, in salt water, lb. per sq. in....	25,000	34,000
Endurance ratio	0 20	0.29

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* McAdam (91)

breaks down the passive film, the corrosion-endurance limit of low-carbon 18-8 becomes a function of the number of cycles. This is clearly shown by the data of Fig. 98. When the specimens were tested in air, the endurance curves became asymptotic at 10^5 and 10^6 cycles; when tested in salt spray, there was no tendency for the curves to become asymptotic at 10^8 cycles. It may be concluded, therefore, that low-carbon 18-8 has no corrosion-endurance limit in salt spray.

Corrosion-endurance limits, determined at 10^7 cycles, were reported by McAdam(91) for two steels containing 17 per cent chromium and 8 and 25 per cent nickel respectively. Results of tests in air, in fresh water, and in river water containing one-third of the NaCl concentration of sea water are given in Table 96.

In an extensive investigation on the effect of steam under 60 lb. pressure and at a temperature of 150°C. (300°F.), Fuller(179) included three 18-8 steels. Their composition, treatment, and endurance limits for 10^7 cycles are given in Table 97. It was concluded that:

> In the hot-rolled condition the endurance values of this alloy bear a relationship to carbon content. This relation, however, disappears after drastic treatment at elevated temperatures. The endurance properties of the 18 per cent chromium, 8 per cent nickel type of alloy are seriously affected by long intervals of time at temperatures of 650°C. (1200°F.) and above.

Haven(228) made torsional fatigue tests on cold-rolled 18-8 streamline wire in air and in carbonate water. The tensile strength and the torsional-fatigue strength in air (27,500 lb. per sq. in.) are given in Table 95. The corrosion-fatigue curve was asymptotic between 10^7 and 10^8 cycles at a stress of 12,000 lb. per sq. in.; *i.e.*, less than half of the value obtained in air. The specimens were tested in the condition in which they came from the cold-rolling mill; hence, the low value for torsional fatigue in air and the still lower value obtained when testing in carbonate water may be explained, in part at least, by the presence of internal stresses and by the presence of stress-raisers on the unpolished surface.

C. CAST AND WELDED AUSTENITIC CHROMIUM-NICKEL STEELS

Resistance to many corrosive media and useful properties at elevated temperatures are characteristic of cast, as well as of wrought, austenitic chromium-nickel steels. Because the cast materials are not hot worked, close control of their chemical composition is not necessary; the carbon, however, is usually held between 0.1 and 0.2 per cent, and for many applications it should be as low as 0.06 to 0.08 per cent.

TABLE 97.—EFFECT OF HEAT TREATMENT ON THE ENDURANCE LIMIT OF 18-8 IN STEAM AT 150°C. (300°F.) AND UNDER 60 LB. PRESSURE*

Steel No.	Treatment of specimen	Endurance limit, lb. per sq. in., of steel containing		
		0.065% C 18.77% Cr 8.91% Ni	0.085% C 18.47% Cr 9.15% Ni	0.15% C 18.24% Cr 8.08% Ni
	Hot rolled	46,000	51,000	56,000
	Air cooled after 6 hr. at 650°C. (1200°F.)	45,000	51,000	46,000
	Air cooled after 500 hr. at 650°C. (1200°F.)	34,000	21,000	40,000
	Air cooled after 1 hr. at 1065°C (1950°F.)	22,500	26,000	26,000
	Treatment 4, plus treatment 2	25,000	22,500	28,000
	Treatment 4, plus treatment 3	25,000	21,000	21,000
	Water quenched after 1 hr. at 1150°C. (2100°F.)	24,000	21,000	34,000
	Treatment 7, plus treatment 2	21,000	21,000	23,000
	Treatment 7, plus treatment 3	21,000	21,000	21,000

* Fuller.(179)

Although the use of austenitic steels for castings is relatively new, Strauss(248) noted that in 1932 most of the alloys included in that corner of the ternary diagram containing up to 40 per cent chromium and about the same amount of nickel had been investigated. As representative of industrial products, he gave typical properties of seven classes of steels containing 0.06 to 0.5 per cent carbon, 8 to 28 per cent chromium, and 8 to 30 per cent nickel. In the cast condition the low-carbon materials are ductile, having elongation values of 20 to 75 per cent and about the same reduction of area. The higher carbon materials are not ductile; according to Strauss, elongation and reduction of area vary between 1 and 10 per cent.

174. Castings with 18 Per Cent Chromium and 8 Per Cent Nickel.—Two grades of 18-8 castings are made: one contains 0.06 to 0.08 per cent carbon; the other between 0.1 and 0.2 per cent carbon; both contain about 19 to 20 per cent chromium and 9 per cent nickel. Typical properties are given in Table 98. The properties determined by Jones were obtained on specimens water quenched from about 1100°C. (2010°F.). He found that, even after quenching, castings containing less than 0.07 per cent carbon tend to be slightly magnetic. There was no trace of magnetic permeability in the higher carbon alloy, which indicates that the promotion of austenite by higher carbon more than offsets liquation or coring effects.

TABLE 98.—PROPERTY RANGES OF 19 PER CENT CHROMIUM, 9 PER CENT NICKEL CASTINGS

Authority	Carbon, per cent	Tensile strength, lb./sq. in	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area per cent	Brinell hardness
Simonds(127).	Less than 0.20	84,000	42,000	47	42	165
Strauss(248).	0.06	70,000 to 80,000	25,000 to 30,000	40 to 75	40 to 75	
	0.15	70,000 to 80,000	25,000 to 40,000	40 to 75	40 to 75	
Jones(376)	Less than 0.07	65,000 to 80,000	32,000 to 40,000	45 to 65	45 to 65	125 to 165
	Less than 0.20	70,000 to 85,000	34,000 to 43,000	40 to 60	40 to 60	130 to 160

The cast low-carbon 18-8 steels have relatively high resistance to single-blow impact. Strauss gave 50 to 105 ft-lb. as average Izod values; Jones reported Izod values as 60 to 100 ft-lb.

Cross(312) determined endurance limits on cast 18-8 alloys containing 0.07 and 0.125 per cent carbon. His data are as shown in the table on page 331. The endurance ratios are considerably higher than those found by other investigators for wrought and quenched materials (see Table 95); on the other hand, tensile strengths, as determined by Cross, are about 20,000 lb. per sq. in. lower than those usually obtained on rolled and quenched steels.

175. Castings with Higher Chromium.—In the United States, castings with more than 18 per cent chromium and 8 per cent nickel are used extensively. These steels frequently contain between 20 and 30 per cent chromium and 10 to 20 per cent nickel, the carbon content ranging from 0.2 to as much as 0.6 per cent, although this high carbon level is unusual.

Property	Carbon, per cent	
	0.07	0.125
Tensile strength, lb. per sq. in.	64,500	64,500
Yield strength, lb. per sq. in.	31,200	28,000
Elongation in 2 in., per cent	59	66
Izod impact, ft-lb.	93	92
Endurance limit, lb. per sq. in.	35,000	36,000
Endurance ratio	0.54	0.56

Probably the greatest tonnage of castings in this category contains about 24 per cent chromium and 12 per cent nickel. The mechanical properties of two such steels are shown in Table 99. Air cooling from 1100°C. (2010°F.) increases the ductility to an appreciable degree; the yield strength is also increased slightly, but the tensile strength is not greatly affected.

Wilcox(410) reported that castings containing approximately 29 per cent chromium and 9 per cent nickel are well suited for resisting corrosion; for heat resistance, the nickel content should be raised to 12 per cent. The mechanical properties of such steels at room temperature are given in Table 100.

176. Effect of Welding on Properties.—The work of Bull and Johnson,(96) Miller,(103) Rollason,(292) Mandran,(327) Hodge,(367) Ragsdale,(396) and others has shown that welds having good mechanical properties can be made in austenitic chromium-nickel steels by any of the well-known processes. The few data given in Table 101 indicate the strength and ductility of welds made by the oxyacetylene and metallic-arc processes.

Satisfactory mechanical properties are obtained easily in flash and spot welds also. Smith(403) obtained elongations of about 50 per cent with a yield strength of 40,000 lb. per sq. in. and a tensile strength of 90,000 lb. per sq. in. in flash-welded thin sections. Ragsdale(396) stated that spot welds in thin sections were twisted from 60 to 90 deg. without failure by shearing, and that spot welding gives a joint about twice as strong as that obtained by riveting which, incidentally, is important in joining very thin sheets.

TABLE 99.—MECHANICAL PROPERTIES OF CAST STEELS CONTAINING (*A*) 0.10 PER CENT CARBON, 0.78 PER CENT MANGANESE, 0.81 PER CENT SILICON, 25.03 PER CENT CHROMIUM, AND 11.53 PER CENT NICKEL AND (*B*) 0.35 PER CENT CARBON, 0.65 PER CENT MANGANESE, 0.85 PER CENT SILICON, 25.97 PER CENT CHROMIUM, AND 12.48 PER CENT NICKEL

Property	Steel *A*		Steel *B*	
	As cast	Air cooled from 1100°C (2010°F)	As cast	Air cooled from 1100°C. (2010°F.)
Tensile strength, lb. per sq. in	80,500	85,000	89,000	88,000
Yield strength, lb. per sq. in..	40,500	46,500	41,000	44,000
Elongation in 2 in., per cent..	43	49	33	39
Reduction of area, per cent..	56	65	27	48
Izod impact, ft-lb.	29	94		
Brinell hardness.	170	146	179	174

TABLE 100.—MECHANICAL PROPERTIES OF CAST STEELS CONTAINING APPROXIMATELY 0.2 TO 0.3 PER CENT CARBON, 29 PER CENT CHROMIUM, AND 9 PER CENT NICKEL*

Steel No.	Composition, per cent					Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
	C	Mn	Si	Cr	Ni				
	0.22	0.27	0.91	28.54	9.92	96,050	47,750	27.0	29.5
	0.26	0.59	1.00	28.60	8.50	97,875	59,000	31.5	30.8
	0.28	0.51	0.84	29.72	8.54	105,350	62,000	23.0	21.3
	0.17	0.57	1.00	27.56	9.51	97,125	46,500	29.0	32.8
	0.33	0.77	1.10	30.34	11.00	97,650	49,000	28.0	28.5

* Wilcox.(410)

Bibber(352) reported tensile tests made on all-weld metal deposited with five different electrodes of 18-8. Average values were as follows:

Property	Base metal, as received	Weld metal, as welded	Weld metal as air cooled from 980°C. (1800°F.)
Tensile strength, lb. per sq. in	85,300	77,900	70,900
Proportional limit, lb. per sq. in	18,500	23,200	19,200
Yield strength, lb. per sq. in.	41,800	53,800	49,800
Elongation in 2 in., per cent	58.8	23.1	18.3
Reduction of area, per cent	70.1	30.3	23.8
Modulus of elasticity, million lb. per sq. in.	30.6	26.5	25.1

They show that the tensile strength of the weld metal is considerably lower than that of the base metal; this is the opposite of the condition usually resulting from arc welding medium-carbon steel with coated electrodes. Ductility values are also lower. However, Bibber considers 25 per cent elongation a good specification value. Elongation values determined across a welded joint are likely to be misleading owing to the greater ductility of the base metal as compared with the weld metal. Bibber's results indicate further that the tensile properties are

Table 101.—Mechanical Properties of Welds Made in Fully Softened Plate of Steel Containing 0.08 Per Cent Carbon, 0.46 Per Cent Manganese, 0.47 Per Cent Silicon, 18.22 Per Cent Chromium, and 8.61 Per Cent Nickel with Rods of the Same Composition

Property	Welding process		
	Oxyacetylene; ¼-in. plate	Metallic arc	
		¼-in. plate	½-in. plate
Tensile strength, lb. per sq. in	76,500	86,900	87,600
Yield strength, lb. per sq. in.	39,200	39,600	40,400
Elongation in 2 in., per cent	25	39	48
Izod impact value, ft-lb.*	. . .	. . . .	80
Transverse bending, deg., without cracking.	180	180	180

* Notch in deposited metal.

lowered by heat treatment. The Brinell hardness of 137 for the welded metal is also lowered somewhat, to about 130, by quenching.

D. MISCELLANEOUS PHYSICAL PROPERTIES

Austenitic chromium-nickel steels differ from pearlitic steels in their stress-strain characteristics and resemble, in this respect, non-ferrous alloys more than ferrous materials. The austenitic steels also differ from carbon and low-alloy steels in their much higher expansion and their much lower thermal conductivity. They are non-magnetic (if wholly austenitic), which is important in many industrial applications.

177. Elastic Properties.—Because there is appreciable curvature of the stress-strain curve, even at very low stress, it is not possible to determine the yield point of the austenitic chromium-nickel steels; yield strength is, therefore, always used as representing the stress corresponding to a definite plastic deformation, usually 0.2 per cent. The curvature of the stress-strain line even at low values of stress makes the determination of the modulus of elasticity particularly difficult, if not impossible. A wide variety of values has been reported ranging from 26.5 million(191) to 29 million lb. per sq. in.* (A value of about 28 million lb. per sq. in. was obtained recently at the Union Carbide and Carbon Research Laboratories.) A popular and useful evasion for the austenitic steels consists of borrowing the "secant modulus" from the testers of cast iron; this is defined as the slope of a straight line connecting the origin of the stress-strain curve with an arbitrary point on that curve. To have any meaning, the stress must be specified when stating a secant-modulus value.

In the cold-worked state, plastic deformation at small loads is marked, and measured tangent moduli as low as 25.5 million are not uncommon, even at relatively low fiber stress. Ffield(357) obtained the data reproduced in Fig. 99. Sutton(475) cited work showing that the precipitation hardening of these steels with a titanium addition results in eliminating this plastic deformation at low loads. He reported a yield strength of 240,000 lb. per sq. in. and a modulus of 29 million lb. per sq. in. after cold working and heat treatment at 480°C. (900°F.). The problem of eliminating this plastic deformation in cold-rolled material

* John Johnston, private communication.

is the subject of intensive research and may well be solved in still other ways in the near future. The fully softened steel has a shear modulus of 11.9 million lb. per sq. in.

The reasons for the relatively high degree of plastic deformation at low stresses, particularly in cold-worked material, have been the subject of considerable speculation; and hypotheses have been advanced relating the phenomenon to warped lattice or even amorphous grain boundaries without particular regard to any austenite-ferrite transformation. There are other theories in which the austenite-ferrite transformation is a major factor.

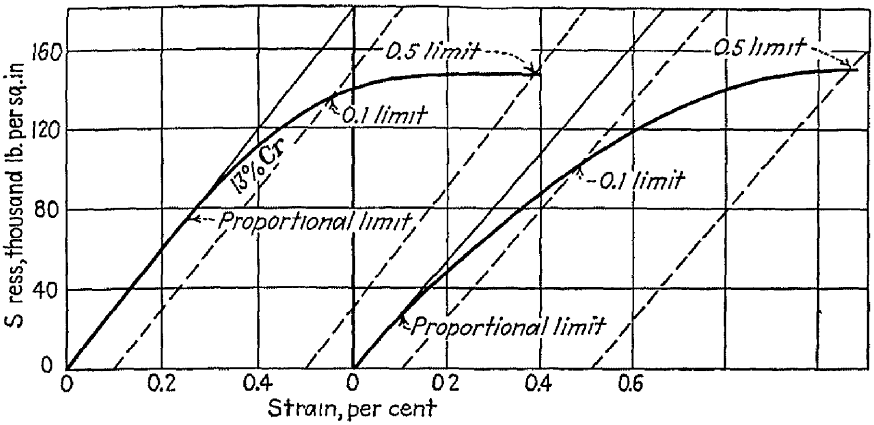

FIG. 99.—Typical stress-strain curve for heat-treated 0.16 per cent carbon, 13 per cent chromium steel and for cold-worked 18-8 containing 0.12 per cent carbon. (*Ffield.*(357))

Bain* suggested an explanation for the particularly low proportional limit found in cold-worked high-strength austenitic stainless steels and the attendant confusion regarding the elastic modulus

> During cold work the austenite progressively transforms to a magnetic constituent which may properly be classed as a low-carbon, high-alloy martensite since the transformation occurs near room temperature, far below the recrystallization temperature for ferrite of such composition. Now the volume of the "martensite" thus formed is greater than that of the austenite from which it formed and it is therefore under compression and, as dispersed, exerts tensional stress upon the remaining austenitic zones. Thus internal stress of high intensity exists in minute regions within the material before any external load is applied. The net stress, applied externally, required to bring local

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* E. C. Bain, private communication.

zones of the tensile specimen to the yield point would necessarily be quite low, below that for pure annealed austenite, and this is in accord with observations at the tensile test.

According to Bain, the unusual circumstance of such marked, distributed, internal stress need cause no difficulty in design, provided actual deflection under various loads is employed rather than a modulus. The endurance limit is high according to tests, and—in good design—the ductility is more than adequate for stress equalization at joints or other stress-raisers. It was stated by Bain that, according to this reasoning, the seeming lack of a definite elastic modulus is a reflection of the circumstances that even low external loads may transgress the range of purely elastic behavior throughout some small parts of the tensile specimen. The generally satisfactory compromise is, therefore, made of reporting and using an unusually low modulus, *e.g.*, 26 million lb. per sq. in., as representing the elongation under a certain stress within the range of usual design.

The extent to which the steel has been cold worked has a marked effect on the measured modulus. However, the application of even small loads causes some plastic deformation so that the measured value is not the true elastic modulus except at zero load. This undoubtedly accounts for most of the variations noted by different investigators in modulus determinations on these steels. This also explains Krivobok's(464) methods of determining the yield stress of the cold-rolled steels of widely varied composition.

The modulus of elasticity of austenitic steel containing 24 per cent chromium and 12 per cent nickel has been reported(485) as 29 million lb. per sq. in. and the modulus of shear as 11.2 million lb. per sq. in.

178. Other Physical Properties.—The density of austenitic chromium-nickel steels of widely varying chromium and nickel contents is between 7.86 and 7.94 g. per cu. cm. The weight in pounds per cubic inch for the low-carbon 18-8 material is given as 0.285 as compared with 0.283 for carbon steel.(482)

Thermal conductivity is given by Shelton(339) as 0.039 cal. per sec. per sq. cm. (°C. per cm.) for the range of 20 to 100°C. (70 to 210°F.); this is approximately one-fourth of the thermal conductivity of high-purity iron and unalloyed low-carbon steels

Shelton's data indicate that the conductivity is affected little, if any, by heat treatment or by increasing the carbon from 0.07 to 0.24 per cent. The value increases with temperature, Shelton reporting 0.042 cal. per sec per sq. cm. at 200°C. (390°F.), 0.045 at 300°C. (570°F.), 0.048 at 400°C. (750°F.), and 0.051 at 500°C. (930°F.). Ranque, Henry, and Chaussain(435) determined the thermal conductivity of a steel containing 0.08 per cent carbon, 19.32 per cent chromium, and 9.55 per cent nickel, after water quenching from 1050°C. (1920°F.). It increased from 0.04 cal. per sec. per sq. cm. (°C. per cm.) at 100°C. (210°F.) to 0.06 at 700°C. (1290°F.). Under comparable conditions, the values for iron containing 0.03 per cent carbon were 0.17 and 0.11; for steel containing 0.30 per cent carbon, they were 0.11 and 0.10.

The thermal conductivity at room temperature of cast austenitic steel containing 25 per cent chromium and 12 per cent nickel is 0.074 cal. per sec. per sq. cm. (°C. per cm.). Geiger(361) reported that the thermal conductivity of wrought low-carbon 25 per cent chromium, 20 per cent nickel steel is 0.052 cal. per sec. per sq. cm. (°C. per cm.).

Austin and Pierce(256) and Souder and Hidnert,(36) among others, made determinations of the coefficient of linear expansion. The values given below, obtained by a manufacturer,(482) are typical for 18-8 and indicate that the coefficients are about 50 per cent greater than for carbon steel.

Temperature range		Mean coefficient of linear expansion, per °C.
°C.	°F.	
20 to 100	70 to 210	0.0000173
20 to 300	70 to 570	0.0000179
20 to 600	70 to 1110	0.0000187
20 to 800	70 to 1470	0.0000194
20 to 1000	70 to 1830	0.0000202

For 24 per cent chromium, 12 per cent nickel steel a coefficient of 20.2×10^{-6} per °C. at 20 to 1000°C. is given.(435) Johnson* reported a somewhat lower value of 17.2×10^{-6}. Cast steel of similar chromium and nickel contents and 0.10 to 0.35

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* J. B. Johnson, private communication.

per cent carbon has a coefficient of linear expansion of 18 × 10^{-6} per °C. for the range 20 to 100°C. and of 20.6 × 10^{-6} per °C. for the range 20 to 1000°C.

179. Electric and Magnetic Properties.—The electric resistivity of softened low-carbon 18-8 as reported by the Allegheny Ludlum Steel Corporation(482) is plotted, as a function of temperature, in Fig. 100. It increases from 77 microhm-cm. at room temperature to 132 at 870°C. (1600°F.). Wrought and cast materials containing 24 per cent chromium and 12 per cent nickel have somewhat higher resistivity; values of 86* and 90 microhm-cm (361) have been reported.

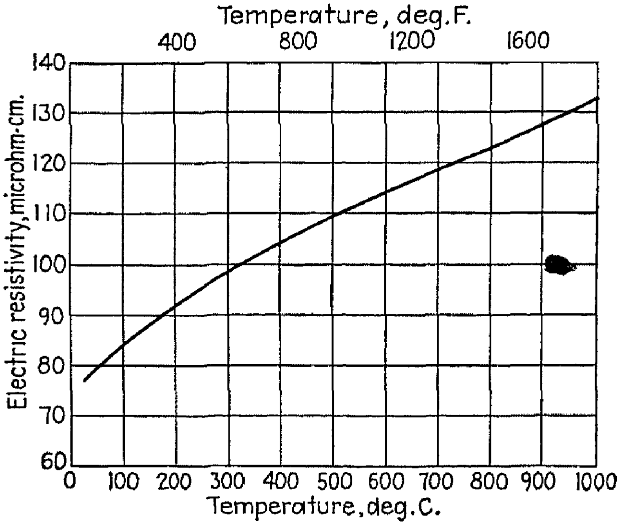

FIG. 100.—Effect of temperature on the electric resistance of softened 18-8. (*Allegheny Ludlum Steel Corporation.*(482))

The fact that austenitic 18-8 alloys have, in addition to high resistance to corrosion, considerable strength and low magnetic permeability makes them useful for such applications as armature binding wire and rope which is in the close vicinity of compasses in marine and aircraft. Magnetic tests have been made also in the attempt to find a simple indicator of corrosion behavior, although they are of doubtful value for this purpose.

Of the small amount of published information, that supplied by the American Society for Testing Materials(210) is probably adequate to show the effect of heat treatment on permeability. Two steels containing (*a*) 0.06 per cent carbon, 18 per cent chromium, and 8.5 per cent nickel and (*b*) 0.085 per cent carbon, 18.73 per cent chromium, and 9.16 per cent nickel were tested (1) as rolled, (2) after annealing for 1000 hr. at temperatures ranging from 425 to 870°C. (800 to 1600°F.), and (3) after water and air quenching followed by annealing. Permeabilities in fields of 200 and 500 oersteds were less than 1.1 for all treatments except

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* Union Carbide and Carbon Research Laboratories.

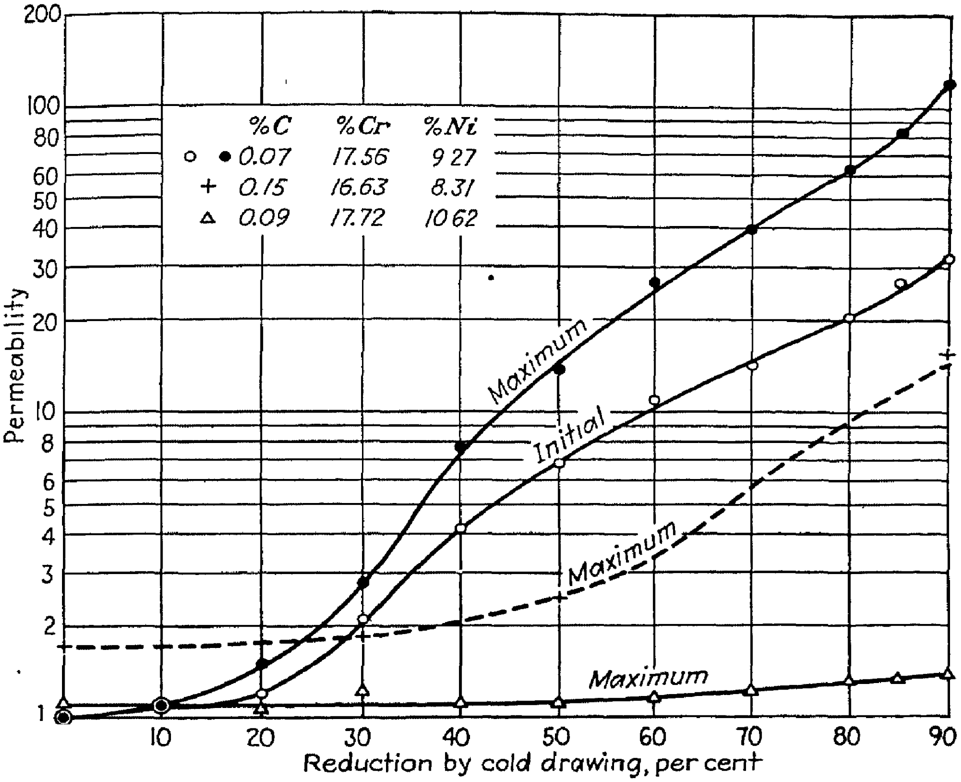

FIG. 101.—Effect of cold work on the permeability of 18-8 (*After Horwedel.*)

those consisting of quenching followed by annealing at 540 to 650°C. (1000 to 1200°F.), for which permeabilities as high as 2.6 were recorded. A specification of permeability less than 1.75 is thus easy to meet in heat-treated material. Cold work induces the separation of ferrite and consequently increases permeability. This is shown by the curves of Fig. 101, which were drawn from data of Horwedel.* Both nickel and carbon increase the persistence of austenite, but since carbon is usually held low, it follows that 8 per cent nickel is not enough to ensure low permeability in heavily cold-worked material. For example, the uppermost curve shows a hundred-fold increase of maximum permeability at 90 per cent reduction for an alloy containing 9.3 per cent nickel. With 10.6 per cent nickel, however, maximum permeability was increased only from 1.2 to 1.4 by 90 per cent cold reduction.

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* C. R. Horwedel, "Magnetic Characteristics of Some Cold-worked Austenitic Iron-chromium-nickel Alloy Wires," Thesis, Ohio State University, 1935, supplied for inclusion in this monograph by courtesy of the author

According to Legge,* the permeability of hard-drawn 18-8 wire is decreased from about 100 to between 3 and 10 if the nickel is increased to 10.5 per cent, and to less than 2 if the nickel is 11 per cent or more.

E. EFFECT OF TEMPERATURE

It is characteristic of austenitic chromium-nickel steels that they maintain toughness at low temperatures and strength at elevated temperatures much better than carbon and low-alloy steels; they are, consequently, suitable for applications involving shock at subzero temperatures or high stresses at elevated temperatures, especially if resistance to oxidation and to certain corrosive media is important.

180. Low-temperature Impact Properties.—It has been shown in other monographs of this series that in most carbon and low-alloy steels the ductility is lowered and there is an almost complete loss of notched-bar impact resistance at some temperature between 0 and −100°C. (30 and −150°F.). The austenitic 18-8 steels, on the contrary, retain their toughness at temperatures as low as −185°C. (−300°F.).

In unpublished impact tests on a steel containing 0.08 per cent carbon, 18.51 per cent chromium, and 9.65 per cent nickel, water quenched from 1100°C. (2010°F.), Izod values between 113 and 119 ft-lb. were obtained at various temperatures between 20 and −185°C. (70 and −300°F.). No change was noted in the impact strength of samples held at −185°C. for as long as 65 hr. and subsequently tested at room temperature. Tests on other austenitic chromium-nickel steels have shown that to maintain toughness under these conditions the steel must have a relatively low carbon content. The ratio of chromium to nickel contents and their absolute values are also important in this connection, as brought out in work by Colbeck and associates.(261) Tests on a steel containing 0.13 per cent carbon, 17.80 per cent chromium, and 7 97 per cent nickel showed an Izod impact value of 118 ft-lb. at room temperature, while at −185°C. the steel had an Izod value of 82 ft-lb. This illustrates the effect of higher carbon content, lower chromium, and higher chromium-nickel ratio. A discussion of the separate effects is given in the original paper.

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* E. E. Legge, private communication.

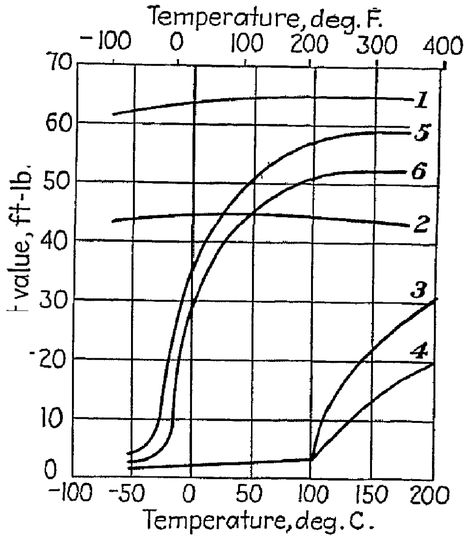

FIG. 102.—Effect of temperature on the impact resistance of low-carbon chromium steel and low-carbon 18-8. (*Sergeson.*(204))

A good comparison of the resistance to single-blow impact of 18-8 and chromium steel containing no nickel is afforded by data reported by Sergeson.(204) Charpy notched-bar (Izod V-notch) impact tests were made at temperatures between −75 and 205°C. (−100 and 400°F.) on steels of the following composition and treatment:

Composition, per cent					Treatment	Curve No.
	Mn	Si	Cr	Ni		
0 08	0.35	0.57	17.52	9.17	Water quenched from 1065°C. (1950°F.)	
					Same, then cold drawn from 1$\frac{1}{16}$ in. to 1 in.	
0 08	0.48	0.50	17 95		Air cooled from 815°C. (1500°F.)	
					Same, then cold drawn from 1$\frac{1}{16}$ in. to 1 in.	
0.10	0.45	0.35	13 31		Furnace cooled from 815°C. (1500°F.)	
					Same, then cold drawn from 1$\frac{1}{16}$ in. to 1 in.	

Results are given in Fig. 102. The high notch toughness of the 18-8 at all temperatures is clearly evident.

Luerssen and Greene(185) studied low-carbon 18 per cent chromium steels containing 4 to 9 per cent nickel after a variety of heat treatments, including cooling the alloys of the border-line type (4 to 5 per cent nickel) to −80°C. (−110°F.) followed by tempering at various temperatures. By quenching in water, treating at −80°C., and tempering at 400°C. (750°F.) the following remarkable combination of strength and impact toughness was obtained:

Property	0.10% C 17.62% Cr 4.03% Ni	0.08% C 17.15% Cr 5.06% Ni
Tensile strength, lb. per sq. in.	209,900	208,000
Yield strength, lb. per sq. in.*	122,000	100,000
Elongation in 2 in., per cent	17.4	19.8
Reduction of area, per cent	64.1	64.3
Brinell hardness	433	444
Izod impact, ft-lb.	46	79

* 0.01 per cent set.

Additional data on the toughness of 18-8 at low temperatures are given in the next section.

181. Low-temperature Tensile Properties.—The low-temperature tensile properties of austenitic chromium-nickel steels depend primarily on how much of the austenite is transformed to martensite. This is shown by the data of de Haas and Hadfield,(264) among others, obtained on a steel containing 0.12 per cent carbon, 18.80 per cent chromium, and 8.10 per cent nickel. The effect of cooling in liquid hydrogen was as follows:

Property	Testing temperature	
	20°C (70°F.)	−215°C. (−355°F.)
Tensile strength, lb. per sq. in.	105,000	263,000
Yield strength, lb. per sq. in.	57,000	122,700
Elongation in 2 in., per cent	56	25
Reduction of area, per cent	53.5	30.5

Colbeck and associates(261) tested low-carbon steels containing 10 to 16 per cent nickel and 12 to 18 per cent chromium and found that in all cases the tensile strength increased as the temperature decreased to −185°C. (−300°F.). In some instances, the strength increased to 2 or 3 times the room-temperature strength. The highest tensile strength and the lowest ductility were shown by those steels whose microstructures exhibited the most martensite after exposure to the low temperature. The steels that remained austenitic had the highest ductility and the lowest strength at the low temperature Mechanical properties, including the endurance limit, at room temperature and at −40°C. (−40°F.), determined for low-carbon 14 per cent chromium and low-carbon 18 per cent chromium, 9 per cent nickel steels by Russell and coworker,(198,199) are given in Table 102. These data show the increase in strength and hardness at −40°C. (−40°F.) and the slight effect this low temperature has on the impact resistance. The increase in tensile strength is not accompanied by a corresponding increase

TABLE 102.—MECHANICAL PROPERTIES AT ROOM TEMPERATURE AND AT −40°C. (−40°F.) OF STEELS CONTAINING (*A*) 0.07 PER CENT CARBON AND 13.85 PER CENT CHROMIUM AND (*B*) 0.09 PER CENT CARBON, 17.51 PER CENT CHROMIUM, AND 9.24 PER CENT NICKEL*

Property	Steel *A*, annealed		Steel *B*, softened†		Steel *B*, cold worked‡	
	20°C. (70°F)	−40°C (−40°F.)	20°C. (70°F.)	−40°C. (−40°F)	20°C. (70°F)	−40°C (−40°F.)
Tensile strength, lb. per sq. in	66,000	75,400	88,000	160,000	127,000	162,500
Yield strength, lb. per sq in ..	....	..	... .	. . ..	114,600	112,400
Elongation in 2 in, per cent ...	40 2	45.0	69.9	48 7	31 5	42.7
Reduction of area, per cent..... ..	75.8	72.9	76 7	70.2	59 5	63.7
Brinell hardness ..	139	148	144	183	260	288
Charpy impact, ft-lb	39	25	80	78	35	30
Endurance limit, lb. per sq. in	39,000	44,000	33,000	42,000	62,000§	75,000
Endurance ratio .	0.59	0.59	0 38	0.27	0.55§	0.46

* Russell(198) and Russell and Welcker (199)

† By water quenching. Specimens for room-temperature tests were 0 5 in, those for cold tests were 0 4 in. in diameter.

‡ Specimens, 0 27 in in diameter, were machined from 0.5-in bar.

§ Determined by J. B. Johnson on 18-8 containing 0.12 per cent carbon.

in endurance limit; consequently, the endurance ratio is some 20 to 30 per cent lower for specimens tested at −40°C.

182. Short-time Elevated-temperature Tensile Properties of Low-carbon Alloys.—Low-carbon austenitic chromium-nickel steels, unlike carbon steels, show no distinct anomalies in short-time tensile properties at 200 to 600°C. (390 to 1110°F.); moreover, unlike carbon steels, for which ductility generally increases and tensile strength decreases with increasing temperature, the low-carbon 18-8 material is usually not so ductile at high temperature as it is at room temperature. This is shown by Newell's(385) data, reproduced in Fig. 103, in which reduction of area for three common tube materials is plotted against temperature. Newell also called attention to the fact that at elevated temperatures 18-8 fails with a brittle fracture, without the warning bulge characteristic of carbon and 5 per cent chromium steels. It is necessary, therefore, when using 18-8 steel tubes to be on guard against sudden failure.

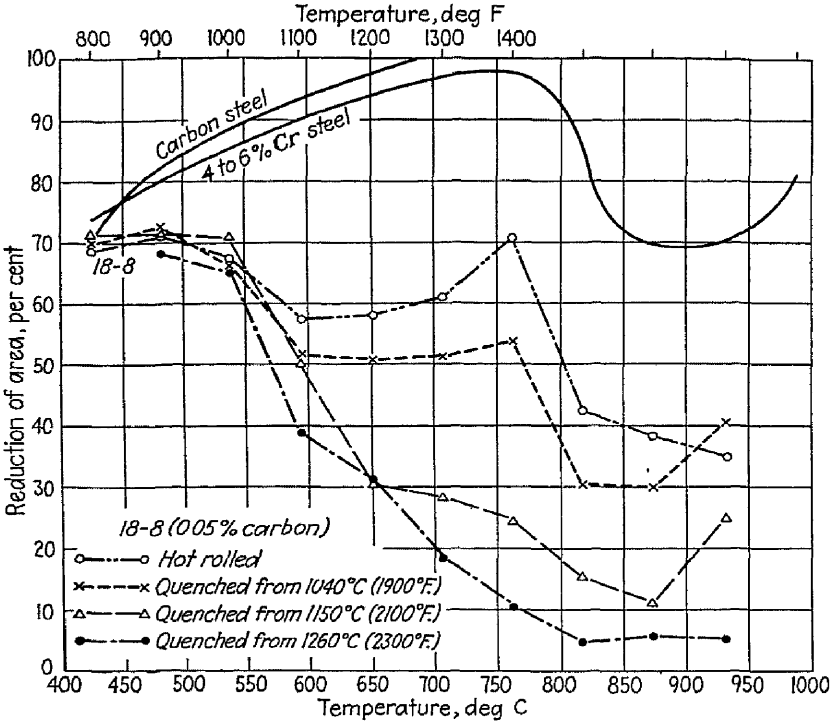

FIG. 103.—Effect of temperature on the reduction of area of tubes of carbon steel, low-chromium steel, and 18-8. (*Newell.*(385))

Data published to 1931 on the short-time tensile properties of low-carbon 18-8 of various analyses, including values supplied by several manufacturers of this material, have been summarized by Aborn and Bain.(167) The outstanding feature of this report, which contains determinations by 14 investigators, is the inconsistency of the results. For material containing less than 0.15 per cent carbon the tensile strength at 800°C. (1470°F.), for example, varies from 18,200 to 43,200 lb. per sq. in. and the elongation in 2 in., from 10 to 55 per cent. Results were just as erratic at other temperatures.

In discussion of a paper by Newell,(194) Strauss and Schafmeister called attention to the importance of testing speed in determining short-time tensile strength and cited the following values for low-carbon 18-8 tested at 800°C. (1470°F):

Time for heating specimen at 800°C. (1470°F.)	Tensile strength, lb. per sq. in.	Elongation, per cent	Reduction of area, per cent
10 sec	42,700	27	36
10 min.	19,900	5	11
42 min	31,300	4	8

They may explain some of the inconsistencies in the data collected by Aborn and Bain.

Short-time tensile properties of 18-8 containing very low carbon, determined by Schmidt and Jungwirth,(244) are given in Table 103. In an effort to avoid what these investigators termed blue brittleness, 0.99 per cent tantalum was added to the steel. Considerable improvement in properties resulted. This paper and the question of blue brittleness in 18-8 and other iron-chromium-nickel alloys are discussed in detail in "The Alloys of Iron and Nickel."(503)*

It is probable that the most reliable data on short-time tensile properties are those published in connection with the correlation of creep data by the Joint Committee of the American Society of Mechanical Engineers and the American Society for Testing Materials.(487) These, together with the creep stresses, are given in Table 108, page 354.

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* Pages 441–445.

TABLE 103.—SHORT-TIME TENSILE PROPERTIES OF LOW-CARBON 18-8, WATER QUENCHED FROM 1100°C (2010°F.)*

Composition, per cent						Testing temperature		Tensile strength, lb./sq. in.	Elongation, $l = 5d$, per cent	Reduction of area, per cent
C	Mn	Si	Cr	Ni	Ta	°C.	°F.			
0.02	0.56	0.57	18.95	7.76	...	20	70	88,200	50.2	58.4
						650	1200	38,500	22.8	36.0
						760	1400	24,900	18.4	26.1
						870	1600	13,100	10.6	13.5
						980	1800	7,600	29.0	27.8
0.04	0.62	0.70	19.02	7.96	0.99	20	70	92,500	49.3	62.0
						650	1200	64,300	33.6	58.8
						760	1400	49,800	31.0	51.0
						870	1600	34,400	17.3	28.0
						980	1800	20,100	16.2	35.0

* Schmidt and Jungwirth.(244)

TABLE 104.—EFFECT OF INCREASED NICKEL ON THE SHORT-TIME TENSILE PROPERTIES OF LOW-CARBON 18-8. THE STEELS CONTAINED (*A*) 0.07 PER CENT CARBON, 18.98 PER CENT CHROMIUM, 8.46 PER CENT NICKEL AND (*B*) 0.07 PER CENT CARBON, 18.78 PER CENT CHROMIUM, 14.66 PER CENT NICKEL*

Testing temperature		Steel *A*			Steel *B*		
°C.	°F.	Tensile strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
20	70	110,000	58	60	85,000		
425	800	66,000	46	70	66,000		
540	1000	60,000	40	68	60,000		
650	1200	50,000	48	65	53,000	40	63
760	1400	25,000	53	55	38,000	46	60
870	1600	13,000	55	43	25,000	38	54
980	1800	7,000	70	50	10,000	50	65

* Pilling and Worthington.(196)

Pilling and Worthington(196) found that increasing the nickel in 18-8 from 8 to 14.5 per cent increased the strength at elevated temperatures; elongation was lowered, and reduction of area was increased slightly. This is shown in Table 104.

TABLE 105.—EFFECT OF CARBON ON SHORT-TIME TENSILE PROPERTIES OF 18-8*

Composition, per cent					Testing temperature		Tensile strength, lb./sq. in.	Yield strength, lb /sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
C	Mn	Si	Cr	Ni	°C.	°F.				
0.04	0.5	0.7	19.02	9.74	20	70	87,300	34,700	61	77
					425	800	64,300	21,500	46	71
					540	1000	59,100	19,500	43	71
					650	1200	52,900	17,000	46	64
					760	1400	25,000	12,000	38	44
					870	1600	19,600	9,500	38	42
0.10	0.5	0.4	19.8	9.53	20	70	94,400	56,100	52	69
					425	800	61,800	34,000	38	66
					540	1000	56,500	34,000	36	69
					650	1200	46,800	33,500	32	66
					760	1400	32,000	22,000	33	45
					870	1600	20,200	10,000	40	52
0.29	0.6	2.5	18.06	9.46	20	70	128,900	61,800	39	53
					425	800	90,900	61,000	25	53
					540	1000	83,200	57,500	25	56
					650	1200	68,900	46,000	32	68
					760	1400	45,900	26,000	44	75
					870	1600	30,400	15,000	43	82

* Aborn and Bain.(167)

183. Effect of Carbon and Grain Size on Short-time Tensile Properties.—Data reported by Edert,(28) Strauss,(56) Hatfield,(101) and Houdremont and Ehmcke,(115) when correlated, indicate that increasing the carbon of 18-8 generally increases the strength and reduces the elongation of the material at elevated temperature. Some of the data reported by these investigators have been summarized by Aborn and Bain.(167) As an example of the effect of carbon, the values supplied Aborn and Bain by the Crane Company are collected in Table 105

Maxwell(433) found that alloys containing (*a*) 0.15 to 0.18 per cent carbon, 25 per cent chromium, and 20 per cent nickel and (*b*) 0.20 per cent carbon, 21 per cent chromium, 12 per cent nickel, 1.5 per cent silicon, and 1.0 per cent copper were resistant to a 3:1 hydrogen-nitrogen mixture for 1535 hr. at 500°C. (930°F.) and under 1000 atmospheres pressure. The strength, elongation, and reduction of area of the high chromium-nickel alloys were unaffected by this treatment; the elongation of the 21 per cent chromium, 12 per cent nickel alloy was lowered in the first 100 hr., but after that there was no change.

TABLE 106.—EFFECT OF TEMPERATURE AND TIME AT TEMPERATURE ON TENSILE PROPERTIES OF 18-8*

Temperature of test		Water quenched from 1040°C. (1900°F.)					
		1 hr. at testing temperature			150 hr. at testing temperature		
°C.	°F.	Tensile strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
A—0.054 per cent carbon, 18.30 per cent chromium, 9.22 per cent nickel							
650	1200	37,500	49.0	50.6	36,700	50.0	65.8
705	1300	28,800	56.0	51.1	35,700	51.0	57.3
760	1400	29,100	49.0	54.0	25,100	40.0	50.6
815	1500	17,900	40.0	31.2	7,500	45.5	43.7
870	1600	11,900	37.5	30.5	15,500	52.5	45.8
925	1700	9,300	52.5	40.8	6,100	58.0	55.8
B—0.14 per cent carbon, 17.41 per cent chromium, 9.56 per cent nickel							
650	1200	51,900	30.0	34.5	54,700	31.0	35.4
705	1300	44,300	26.5	31.3	46,400	35.0	36.7
760	1400	32,100	45.0	44.7	21,400	65.0	58.8
815	1500	23,100	23.5	29.7	24,400	31.5	36.3
870	1600	16,100	37.0	33.9	17,100	42.0	35.3
925	1700	12,500	35.5	38.7	16,300	35.0	39.1

* Newell.(194)

Data reported by Newell(194) indicate that the grain size of 18-8 has a marked effect on elevated-temperature tensile properties. He water quenched specimens from various temperatures and tested them after holding 1 and 150 hr. at the testing temperature. The testing speed was 0.08 in. elongation per min. Some of the results are given in Table 106. Newell concluded that

> the ductility of both 0.05 and 0.14 per cent carbon 18-8 alloy on rupture at elevated temperature is greatly affected by the grain size of the metal. Fine-grained alloys show much more ductility than do coarse-grained ones at temperatures in the range 595 to 925°C. (1100 to 1700°F.). Short-time tensile strength is also affected.

Table 106.—Effect of Temperature and Time at Temperature on Tensile Properties of 18-8.*—(*Continued*)

Temperature of test		Water quenched from 1260°C. (2300°F.)					
		1 hr. at testing temperature			150 hr. at testing temperature		
°C.	°F.	Tensile strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
A—0.054 per cent carbon, 18.30 per cent chromium, 9.22 per cent nickel							
650	1200	35,900	26.0	31.2	35,200	34.0	34.2
705	1300	25,800	14.0	13.0	36,400	32.0	34.2
760	1400	21,100	8.5	10.4	23,600	19.0	26.5
815	1500	15,900	8.5	5.0	5,900	12.0	15.6
870	1600	14,700	6.5	5.9	14,700	17.5	24.1
925	1700	7,600	7.0	5.8	5,400	22.0	13.8
B—0.14 per cent carbon, 17.41 per cent chromium, 9.56 per cent nickel							
650	1200	46,800	23.0	23.9	46,900	20.0	25.5
705	1300	40,500	15.0	17.1	42,900	17.5	38.8
760	1400	29,300	21.0	19.9	31,000	36.0	41.9
815	1500	23,100	14.0	13.8	23,400	20.0	22.3
870	1600	9,300	28.0	25.4	16,800	26.0	30.0
925	1700	12,800	28.5	26.1	15,300	36.0	33.4

184. Other Short-time Elevated-temperature Properties.—Tests of 18-8 springs at elevated temperatures in comparison with similar springs made of heat-treated carbon, chromium-vanadium, chromium, and high-speed steels were reported by Zimmerli, Wood, and Wilson.(305) All springs were coiled from cold-drawn wire and were blued at 425°C. (800°F.). It was found that under loads of 40,000 lb. per sq. in., the 18-8 and the 0.30 per cent carbon, 12.6 per cent chromium steel can be used at temperatures up to 260°C. (500°F.) without losing more than 4 per cent load. The carbon and low-alloy steels can be used at temperatures up to 95°C. (200°F.) only, or—under lower stresses—up to 205°C. (400°F.). The high-speed steel withstood high stresses at temperatures up to 370°C. (700°F.).

In work on torsional strength at elevated temperatures Sauveur(160) included two austenitic steels of the following analyses:

Steel	Composition, per cent				
	C	Mn	Si	Cr	Ni
A	0.08	0 35	0.36	17.20	8 61
B	0.18	0 59	1.24	7 66	19 83

As this investigation is discussed in detail in "The Alloys of Iron and Nickel,"(503) the results may be summarized by stating that at 540 to 815°C. (1000 to 1500°F.) steel *A* had a slightly higher torsional strength than steel *B* despite the lower carbon content; it was also more ductile in the temperature range 540 to 730°C. (1000 to 1345°F.), but steel *B* was more ductile than *A* at higher temperatures.

185. Short-time Elevated-temperature Properties of Cast Austenitic Chromium-nickel Steels.—Since cast chromium-nickel steels containing 15 to 30 per cent chromium and 0 to 65 per cent nickel are widely used in applications involving high temperatures, their properties at these temperatures are of much interest. Some of the data on short-time and creep properties of these materials are summarized in a previous monograph.(503)

As time is a very important factor in elevated-temperature service, investigators of the properties of cast austenitic material have naturally paid most attention to creep. Representative short-time data, reported by the Joint Research Committee, are given in Table 109, page 357. The values for the 0.067 and 0.125 per cent carbon steels were published previously by Cross.(312) An interesting conclusion to be drawn from Cross's work is that the endurance ratio for N^8 cycles is the same (0.55 to 0 57) at 650°C. (1200°F.) as at room temperature.

A large part of the tonnage of cast austenitic material consists of alloys containing more chromium and nickel than the 18-8 grade. Pilling and Worthington(196) gave data, supplied to them by the Ohio Steel Foundry Company, on a cast alloy containing 0.4 per cent carbon, 0.8 per cent silicon, 26 per cent chromium, and 11 per cent nickel. Significant changes in tensile strength with temperature are as follows:

Temperature of test		Tensile strength, lb. per sq. in.
°C.	°F.	
Room		64,000
540	1000	60,000
650	1200	55,000
760	1400	49,000
870	1600	39,000
980	1800	20,000

In general, the elongation and reduction of area of cast steels of this type are low but increase somewhat at temperatures of 800°C. (1470°F.) and above. Pilling and Worthington noted that at temperatures of 650°C. (1200°F.) or above, the "strengths of wrought and cast material under quick loading are approximately the same."

Properties at elevated temperatures of cast 24 to 29 per cent chromium, 12 per cent nickel alloys have been reported by Wilcox(410) and by Roush and Dames.(505) Both gave 20,000 lb. per sq. in. as the strength at about 870°C. (1600°F.).

186. Creep Data of Wrought Low-carbon Austenitic Chromium-nickel Steels.—The creep strength of 18-8 has been the subject of extensive study. Since the review in another monograph of this series(503) of data for alloys containing more nickel than chromium the valuable collection of data by the Joint Research Committee(487) has been issued, which makes a similar review of reported data on 18-8 alloys unnecessary. It seemed advisable, however, to enumerate, chronologically, for ready reference, the work by the principal investigators in this field.

They are: French, Cross, and Peterson,(82) Norton,(120) Hatfield,(142) Clark and White,(175) Kanter and Spring,(148) French, Kahlbaum, and Peterson,(137) Rosenhain and Jenkins,(157) Spring,(206) Jenkins and Tapsell,(184) Newell,(193,385) Bailey, Dickenson, Inglis, and Pearson,(170) McNiff,(186) Barr and Bardgett,(214) Müller-Berghaus,(328) Cross,(312) Musatti and Reggiori,(329) Wright,(414) Grunert and Rohn,(423) and Cross and Lowther.(449) In addition to these, the summaries of data collected by Strauss,(162) Aborn and Bain,(167) and Pilling and Worthington(196) should be mentioned.

In general, creep stresses for low-carbon 18-8 as reported in the recent literature vary between the following limits:

Temperature		Creep stress, lb. per sq. in., for an elongation of 1 per cent in	
°C.	°F.	10,000 hr.	100,000 hr.
425	800	....	24,000 to 30,000
540	1000	17,000 to 25,000	10,000 to 14,000
650	1200	7,000 to 9,000	4,000 to 6,000
730	1350	2,000 to 3,000	1,500 to 2,000

Although Kanter and Spring(148) recognized as early as 1930 that many variables in the prior history of an alloy are important in influencing resistance to creep, most investigators have neglected to pay attention to these factors; this may account for some of the variation in reported values. Figure 104 shows creep values which are recommended for use in conservative engineering design. Strauss(162) gave the following as the safe working stress, in pounds per square inch, for a mean creep rate of 1 per cent in 8 years (70,000 hr.): 10,000 at 540°C. (1000°F.), 4000 at 650°C. (1200°F.), 2600 at 705°C. (1300°F.), and 1350 at 760°C. (1400°F.).

The creep strength, and some short-time tensile properties, of a series of 18 per cent chromium, 8 per cent nickel steels, as summarized by the Joint Research Committee,(487) are reproduced in Table 108. The composition, thermal treatment, and other pertinent details concerning the specimens are collected in Table 107. The creep-stress values of Table 108 are undoubtedly the best available, but it is evident that much work remains to be done before the creep strength for rates of 0.1 and 0.01 per cent elongation in 1000 hr. can be fixed with certainty. The most that can be said at present is that austenitic chromium-nickel steels have 3 to 10 times the creep strength of pearlitic and ferritic carbon and alloy steels, and that the addition of 8 per cent or more nickel triples the creep strength of the high-chromium steels between 600 and 1000°C. (1110 and 1830°F.).

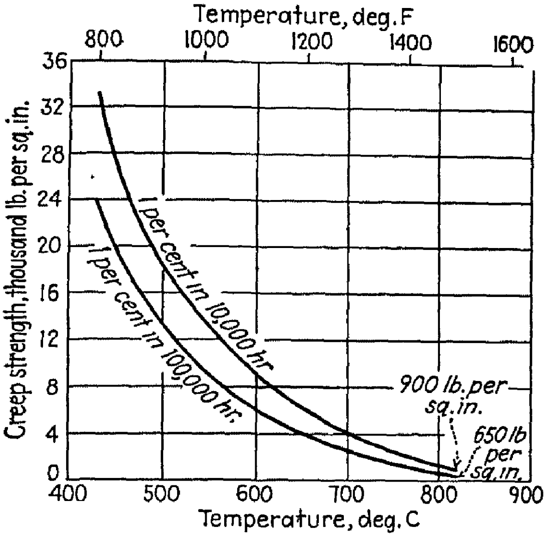

FIG. 104.—Creep stresses for 0.1 and 0.01 per cent elongation in 1000 hr. for low-carbon 18-8, to be used in conservative engineering design. (*Allegheny Ludlum Steel Corporation.*[(482)])

TABLE 107.—COMPOSITION, HEAT TREATMENT, AND OTHER DETAILS OF SPECIMENS WHOSE PROPERTIES ARE GIVEN IN TABLE 108*

No	Composition, per cent					Water quenched from		Kind of steel	Remarks
	C	Mn	Si	Cr	Ni	°C.	°F		
2A	0.09	0.32	0.28	17.75	8.54				Cold rolled
2C	0.04	0.50	0.70	19.02	9.74	1150	2100		
2D	0.10	0.51	0.51	19.82	9.35	1095	2000		
3	0.06	0.50	0.61	17.75	9.25	1095	2000	Basic arc	Killed with silicon
10*A*	0.125	0.47	0.58	18.50	9.67	1095	2000	Acid induction	Killed with CaSi + Al
10*C*	0.067	0.50	0.65	18.21	9.56	1095	2000	Acid induction	Same as 10*A*
12	0.15	0.23	0.37	17.20	7.	Not given			

* Joint Research Committee (487)

TABLE 108.—SHORT-TIME TENSILE AND CREEP PROPERTIES OF LOW-CARBON 18-8*

No.	Testing temperature		Tensile strength, lb./sq in.	Yield strength, lb./sq in.	Proportional limit, lb /sq in.	Elongation in 2 in , per cent	Reduction of area, per cent	Creep stress, lb. per sq. in , for an elongation of 1 per cent in	
	°C.	°F.						10,000 hr.	100,000 hr.
2*A*	650	1200	58,500	44,500	29,500	25.0	61.7	4,500	
2*C*	760	1400	30,300	13,000	6,500	30.0	38.8	3,000	
2*D*	20	70	85,600	52,200	19,000	62.0	75.2		
	425	800	61,800	34,000	23,000	37.5	66.4		
	540	1000	56,500	34,000	21,500	35.5	69.1	24,000	
	650	1200	46,800	33,500	22,000	32.0	66.0		
	760	1400	32,000	22,000	12,000	33.0	45.4	4,800	
	870	1600	20,200	10,000	5,000	40.0	52.3		
3	30	85	85,200	27,900	12,500	61.5	74.4		
	425	800	...	.....	....	..	..	.....	10,800
	480	900	56,900	14,700	8,100	45.0	69.3	.	4,000
	540	1000	53,800	14,500	7,500	44.0	70.5	18,000	1,500†
	595	1100	48,800	12,400	7,500	39.0	58.0	13,000	
	650	1200	43,100	11,000	6,300	37.0	44.3	8,500	
	705	1300	25,300	11,000	5,600	35.0	36.5		
	760	1400	27,800	10,800	5,000	31.3	28.5		
	815	1500	..	......	......	.....	..	3,000	
10*A*	Room		91,000	41,000	......	60.5	71		
	480	900	...	....	.....	...	....	.	16,000
	540	1000	.....	....	.	50.0	66	24,800	
	595	1100	..	.....	......	....	..	17,000	
	650	1200	......	......	.....	34.5	40	10,500	
10*C*	Room		85,000	35,500	......	61.5	70.5		
	540	1000	...	..	..	..	..	20,000	
	650	1200	......	.....	......	.....	.....	8,000	
12	18	65	115,400	40,100	17,900	64 ‡	56		
	300	570	74,000	22,400	7,400	52 ‡	68.5		
	400	750	72,200	20,200	7,400	59.5‡	71		
	500	930	67,200	......	.....	52 ‡	69	20,000	
	600	1110	58,300	....	......	54 ‡	65.5		

* Joint Research Committee.(487)

† At 565°C. (1050°F.).

‡ Elongation in $4\sqrt{A}$.

The higher alloy steels have greater creep strength than the 18-8 steels. Creep-stress data up to 815°C (1500°F.) for 20 to 25 per cent chromium, 12 to 20 per cent nickel steels are given in Figs. 105 and 106. The curves bring out clearly that the wrought 24 per cent chromium, 12 per cent nickel steel is stronger at temperatures up to 815°C. (1500°F.) than 18-8 material.

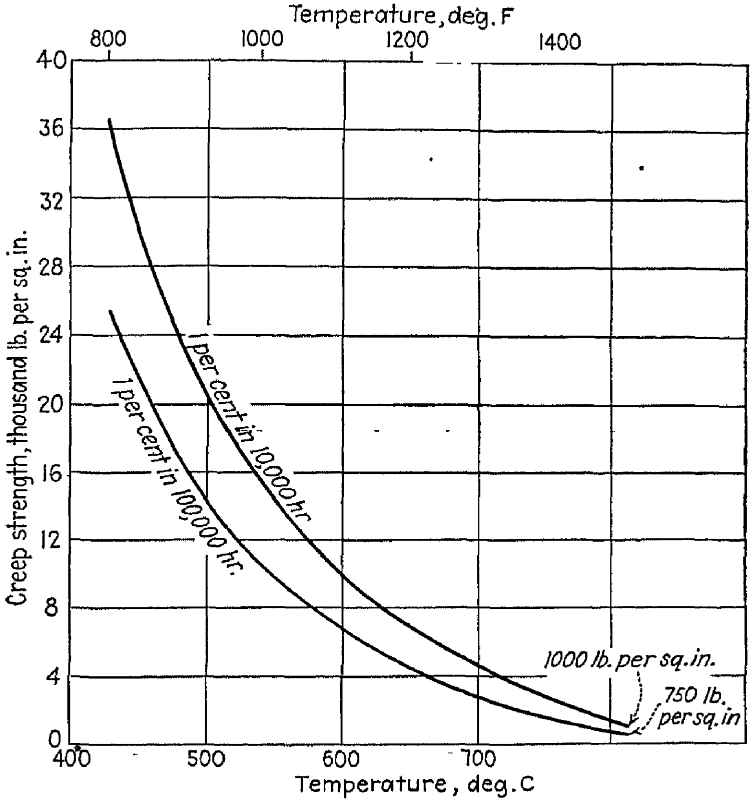

FIG. 105.—Creep stresses for 0.1 and 0.01 per cent elongation in 1000 hr. for steel containing 24 per cent chromium and 12 per cent nickel. (*Allegheny Ludlum Steel Corporation.*[485])

187. Creep Data on Cast Austenitic Chromium-nickel Steels.—The creep stress for 0.1 per cent elongation in 1000 hr. of two cast 18-8 steels, determined by Cross for the Joint Research Committee,[487] is given in Table 109. These data and those of Table 108 permit a comparison of the creep strength of identical material as determined on cast and wrought specimens. The corresponding values are as follows:

Condition	Temperature		Creep stress, lb. per sq in., for 1 per cent elongation in 10,000 hr.	
	°C.	°F.	0.067% C	0.125% C
Wrought	540	1000	20,000	24,800
Cast . .	540	1000	14,500	22,500
Wrought	650	1200	8,000	10,500
Cast. . .	650	1200	8,500	9,000

A large part of the data on creep of cast alloys published up to 1933 has been summarized by Stanbery(296) who, after correlating all the data, plotted a series of "design-stress curves" for five classes of alloys. Two of these cover materials containing more chromium than nickel; the composition ranges are as follows: class *A*, 0.3 to 0.5 per cent carbon, 25 to 30 per cent chromium, 18 to 25 per cent nickel and class *B*, 0.20 to 0.35 per

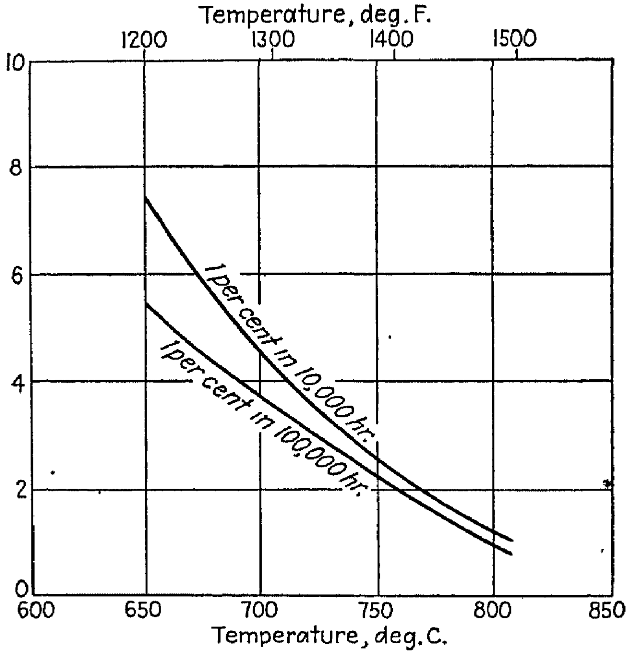

FIG. 106.—Creep stresses for 0.1 and 0.01 per cent elongation in 1000 hr for steel containing 25 per cent chromium and 20 per cent nickel. (*Babcock and Wilcox Tube Company.*(347))

TABLE 109.—SHORT-TIME TENSILE AND CREEP STRENGTHS OF SEPARATELY CAST SPECIMENS OF KEELBLOCKS OF 18-8*

Composition, per cent					Water quenched from		Testing temperature		Tensile strength,	Yield strength lb /sq.	Proportional limit, lb./sq.	Elongation in 2 in., per cent	Reduction of area, per cent	Creep stress, lb./sq in †
	Mn	Si	Cr	Ni	°C.	°F.	°C.							
0 10	0.48	0 28	18 72	10 00	1040	1900	20	70	71,400	30,800	18,300	55 0	62 5	
							425	800	58,000	18,000	5,000	47 0	56 2	
							540	1000	51,800	14,500		39 0	47 8	
							650	1200	41,000	14,000		29 5	41 8	
							760	1400	24,900			13 5	23 4	
							870	1600	16,000			16 0		
0 067	0.50	0.65	18 21	9.56‡	1095	2000	Room		64,500	28,000	36,000§	66 0		
							540	1000	44,600			44 0	59 5	14,500
							650	1200	37,000		20,000§	39 0	55 0	
0 125	0 47	0 58	18.50	9 67‖	1095	2000	Room		64,500	31,200	35,000§	59 0		
								900	54,600			50 0	57 5	
							540	1000	49,300					22,500
							595	1100				38 0	40 2	17,000
							650	1200	40,400		23,000§	37 0	50 5	9,000

* Joint Research Committee.(487)

† For an elongation of 1 per cent in 10,000 hr.

‡ Same as steel 10*C* in Table 108.

§ Endurance limit

‖ Same as steel 10*A* in Table 108.

cent carbon, 25 to 30 per cent chromium, and 8 to 15 per cent nickel. Values taken from the curves for an expected creep of 1 per cent in 10,000 hr. are as follows:

Temperature		Creep stress, lb. per sq. in.	
°C.	°F.	Class *A*	Class *B*
540	1000	20,000	11,000
595	1100	10,000	7,000
650	1200	6,000	4,000
705	1300	4,000	2,800
760	1400	2,800	2,000

In connection with these values Stanbery stated:

The curves are frankly extrapolations from scanty information and guesses as to the facts. Furnace parts so designed have, however, given such service as to indicate that the curves are a happy medium between too optimistic and too pessimistic designing.

Stanbery's results indicate that increasing the nickel from about 12 to about 20 per cent increases the creep strength. The higher nickel alloys (35 to 65 per cent) with 18 per cent chromium had approximately the same creep strength as the alloys of class *A*. The alloys containing 24 to 28 per cent chromium and no nickel had, however, a lower creep strength at temperatures of 540°C. (1000°F.) and above than either class *A* or *B*.

Tucker and Sinclair(299) determined the stress producing 1 per cent creep in 10,000 hr. at 870°C. (1600°F.) on two high chromium-nickel steels containing (*A*) 0.03 per cent carbon, 0.28 per cent manganese, 0.54 per cent silicon, 17.20 per cent chromium, and 24.00 per cent nickel, for which the creep stress was 1300 lb. per sq. in., and (*B*) 0.26 per cent carbon, 0.27 per cent manganese, 1.10 per cent silicon, 30.94 per cent chromium, and 33 per cent nickel, for which the creep stress was 2400 lb. per sq. in. According to these investigators, the best iron-chromium-nickel alloy for creep resistance at elevated temperature should contain equal parts of these three metals.

F. AUTHORS' SUMMARY

1. Hot-worked low-carbon 18 per cent chromium, 8 per cent nickel steels have a tensile strength of 80,000 to 100,000 lb. per sq. in., a yield ratio of 30 to 50 per cent, and high elongation, reduction of area, and impact resistance. Cold rolling increases the strength and decreases the ductility and toughness.

2. The heat treatment widely used for 18-8 is a softening by rapid cooling from 1000 to 1200°C. (1830 to 2190°F.). This produces a wholly austenitic structure with all carbides in solution. A very high quenching temperature results in grain growth which is evidenced by lower strength and somewhat higher ductility. It also makes the material more difficult to fabricate. Alloys containing more than 0.09 per cent carbon are greatly damaged by long heating at high temperatures. This causes excessive carbide precipitation and greatly reduced impact resistance.

3. Low-carbon 18-8 is readily cold drawn into wire or cold rolled into strip. The properties of the finished product depend upon the amount of cold working and upon the final size. Ten-

sile strengths of 250,000 to 400,000 lb. per sq. in. can be attained; elongation and reduction-of-area values for drastically cold-worked material are low.

4. Increasing the nickel of the low-carbon 18-8 increases the stability of the austenite; and increasing both chromium and nickel increases elevated-temperature strength. At room temperature, the properties of these high-alloy steels are about the same as those of the 18 per cent chromium, 8 per cent nickel material.

5. Fully softened 18-8 has an Izod impact resistance of 100 to 120 ft-lb., which is unaffected by heat treatment, provided there is no carbide precipitation. In contrast to carbon and most alloy steels, low-carbon 18-8 retains its notch toughness at temperatures as low as −185°C. (−300°F.).

6. The endurance ratio of the rolled material is about 0.50, but this is lowered by quenching. Carbon and grain size have little effect on endurance ratio; cold working, however, increases it.

7. The corrosion endurance of 18-8 depends upon the corroding medium. In fresh water, the endurance limit is about the same as when determined in air; in a salt spray or other corrosive agent which breaks the passive surface film, the endurance limit is a function of the number of cycles.

8. Castings of 18-8 with less than 0.20 per cent carbon, and those with 20 to 30 per cent chromium, 10 to 20 per cent nickel, and 0.2 to 0.6 per cent carbon, are widely used industrially. Their tensile strength after water quenching is about the same as that of wrought material; elongation, reduction of area, and impact resistance are slightly lower.

9. The 18-8 alloy is readily welded by any of the usual processes, but the joint may require heat treatment to restore the properties of the base material. Elongation and reduction of area are considerably lower in the weld than in the heat-treated material, but they are rarely less than 25 per cent.

10. Fully softened 18-8 has a modulus of elasticity of approximately 28 million lb. per sq. in. and a low proportional limit. A value of 26 million lb. per sq. in. for the secant modulus of cold-worked material is used frequently in design. Data on density and other physical constants, and on electric and magnetic properties, are also summarized in this chapter.

11. The tensile strength of the softened material decreases from about 90,000 at room temperature to about 10,000 lb. per sq. in. at 760°C. (1400°F.). Elongation and reduction of area are lower at elevated temperature than at room temperature. Increasing the carbon increases the elevated-temperature strength and reduces elongation. Cast alloys have approximately the same short-time elevated-temperature properties as wrought alloys.

12. Low-carbon 18-8 has a creep stress, for 1 per cent elongation in 10,000 hr., of at least 3 times, and in some cases 10 times, the creep strength of pearlitic and ferritic steels. The addition of 8 per cent or more nickel triples the creep strength of the high-chromium steels in the temperature range 600 to 1000°C. (1110 to 1830°F.). Much remains to be done before the actual stress for creep rates of 0.1 and 0.01 per cent in 1000 hr. can be stated with certainty.

CHAPTER XII

THE RESISTANCE OF THE AUSTENITIC CHROMIUM-NICKEL STEELS TO OXIDATION AND CORROSION

Oxidation of Chromium-nickel Steels—Corrosion of Chromium-nickel Steels in Various Media—Pitting and Intergranular Corrosion—Corrosion in Internal-combustion Engines—Authors' Summary

The resistance of high-chromium steels to oxidation and corrosion is unique in the field of ferrous alloys, and their usefulness in engineering design and construction is largely predicated on this specific property. Although oxidation resistance and corrosion resistance are not necessarily coexistent, they are closely allied, so that they may be grouped broadly as manifestations of the same group of phenomena. Although the common cause may be basic in that it is a direct function of chemical constitution, differences in degree within certain broad limits may be produced by modifications of composition. Probably the most important modification of high-chromium steels from an industrial standpoint is the introduction of nickel, which forms a solid solution with chromium and iron. Nickel in moderate amounts has little effect on oxidation resistance, but it plays an important rôle in improving other properties in the application of the material at temperatures usually promoting oxidation. On the other hand, nickel has a most important influence on corrosion resistance, particularly to media of relatively low oxidizing power. In general, then, corrosion resistance is improved by nickel; but nickel renders the steel austenitic, and, as discussed in Chapter IX, some austenitic chromium-nickel steels tend to revert to ferrite at moderately elevated temperatures. Moreover, under certain temperature conditions, carbon is rejected from solid solution with formation of a grain-boundary precipitate which results in localized susceptibility to corrosive attack. The result of such attack is commonly known as intergranular corrosion. In this chapter the effect of nickel on the oxidation and corrosion resistance of high-chromium steels and the subject of intergranular corrosion are discussed in detail.

A. OXIDATION OF CHROMIUM-NICKEL STEELS

The progressive rusting or oxidation of iron and steel is a common experience. Rusting at ordinary temperatures differs in certain respects from scaling at elevated temperatures, where the rate of reaction of the oxygen in the air with the iron is increased and the metal is much more rapidly converted to oxide Gases present in the atmosphere of industrial furnaces, such as sulphur dioxide, carbon dioxide, and water vapor, are likewise oxidizing so that iron may react rapidly as the temperature increases even though molecular oxygen is substantially absent

188. Oxidation Resistance at Elevated Temperatures.—In 1920, Johnson(19) described non-magnetic, flame-resisting chromium-nickel steels suitable for resisting oxidation up to about 1100°C. (2010°F.), but information regarding their composition was withheld. His investigation led to the development of the high-silicon heat-resisting chromium-nickel steels, which are treated at greater length in a subsequent chapter. Later, Hadfield and Sarjant(100) and Hatfield(86) published comprehensive data on the composition of heat-resisting steels. The former reported that steels of this type usually contain 10 to 30 per cent chromium, 7 to 40 per cent nickel, and 70 to 50 per cent iron, with small additions of other elements. They pointed out that they are stronger than ordinary steel and cast iron as well as more oxidation-resistant at elevated temperatures Hatfield tested 18-8 and 21-10 chromium-nickel steels at temperatures between 700 and 1000°C. (1290 and 1830°F.) and found that the former were relatively resistant to oxidation at the lower temperatures, while the latter were particularly resistant at the higher temperatures investigated.

Heat-resistant chromium-nickel steels are employed as wrought products and as castings, with carbon contents varying over a wide range. The oxidation resistance of the 18-8 steels is industrially satisfactory at temperatures up to 800 or 900°C. (1470 or 1650°F.), while that of the 24-12 and the 25-20 steels is sufficient for industrial purposes up to 1100°C. (2010°F.). The data in Table 110 show the comparative resistance of typical steels to atmospheric oxidation at elevated temperatures.

They were obtained by exposing weighed, descaled samples (approximately ⅞ in. in diameter by 1.5 in. in length) to the temperatures indicated, for a period of 1 week. The samples were then cooled to room temperature in the furnace and weighed after removal of the loose scale. The specimens held for 600 hr. (3 weeks, 4 days) were cooled each week so that the losses shown are probably greater than would have been obtained on samples held continuously. Austenitic chromium-nickel steels have a high coefficient of expansion, which promotes scale cracking and flaking on heating and cooling. This means that the more frequently the metal is heated and cooled the greater will be the oxidation.

TABLE 110.—OXIDATION TESTS OF CHROMIUM-NICKEL STEELS IN AIR

Composition, per cent					Weight loss, per cent, after 600 hr. at		Weight loss, per cent, after 168 hr. at	
C	Mn	Si	Cr	Ni	800°C. (1470°F.)	900°C. (1650°F.)	1000°C. (1830°F.)	1100°C. (2010°F.)
0.15	.	....		...	42			
0.11	0.56	0.25	18.69	8.46	0.51	0.96	13.30	
0.20	0.78	0.65	24.16	11.54	0.10	0.66	0.30	0.37
0.15	0.62	0.75	24.96	21.55	....	0.48	0.25	0.32

The data of Table 110 show that, in comparison with low-carbon steel, all the chromium-nickel steels are markedly oxidation resistant. The 25-20 steel is a little more resistant than the 24-12 steel. The chief advantage of the higher nickel steel is its greater creep strength; this is discussed in Chapter XI. If resistance to shock is important, the more highly alloyed steels should contain less than 0.15 per cent carbon and the 18-8 steel preferably not more than 0.10 per cent, but when only oxidation is to be considered, the carbon content may be 0.50 per cent or higher.

The resistance of these steels to oxidation is due primarily to their chromium content. Baeyertz(418) expressed the opinion that at the elevated temperatures two or more oxides high in chromium are formed on the surface of the metal. This apparently prevents further penetration of the oxygen. She also claimed that the oxides formed are of widely different composition, depending on the temperature of formation and the chromium content of the alloy.

189. Resistance to Sulphur-bearing Compounds at Elevated Temperature.—The rate of scaling at elevated temperatures is greatly influenced by sulphur-bearing compounds in the atmosphere to which the steels are exposed. Under some conditions the chromium-nickel steels are industrially unsuitable because of susceptibility to sulphur attack. This depends upon the concentration of compounds of this element in the atmosphere and on the temperature of exposure. Kaysèr(39) and Wellmann(208) attributed the effect of sulphur compounds to the formation of nickel sulphide which melts at about 650°C. (1200°F.). In considering the rate of attack by sulphur-containing gases, it is important to distinguish between scaling in hydrogen sulphide—either pure or mixed with non-oxidizing gases—and scaling in mixtures of sulphur dioxide and oxidizing gases such as oxygen, water vapor, or carbon dioxide.

Comparatively little information on this subject is available; the experimental data given in Table 111, obtained on an 18-8 steel, show that hydrogen sulphide is decidedly more active at elevated temperatures than sulphur dioxide. These data are

TABLE 111.—EFFECT OF SULPHUR AND ITS COMPOUNDS, AT ELEVATED TEMPERATURES, ON A STEEL CONTAINING 0.10 PER CENT CARBON, 0.47 PER CENT MANGANESE, 0.23 PER CENT SILICON, 18.45 PER CENT CHROMIUM, AND 8.56 PER CENT NICKEL

Corroding agent	Temperature of test		Duration of test, hr.	Weight loss, per cent
	°C.	°F.		
Molten sulphur	140	285	24	Nil
Moist SO_2 gas	600	1110	166	0.05
	900	1650	24	2.18
Moist H_2S gas	300	570	158	0 052
	600	1110	65	4 30
	900	1650	21	
H_2S gas (1 part) plus nitrogen (10 parts)	600	1110	65	2.08

* Metal converted to sulphide.

particularly striking because 18-8 steel suffers practically no loss in weight upon exposure at 600°C. (1110°F.) to a simple oxidizing atmosphere and is relatively resistant at 900°C (1650°F.), while at 600°C. (1110°F.) in moist hydrogen sulphide gas it lost about 5 per cent in weight, and at 900°C. (1650°F.) it was converted

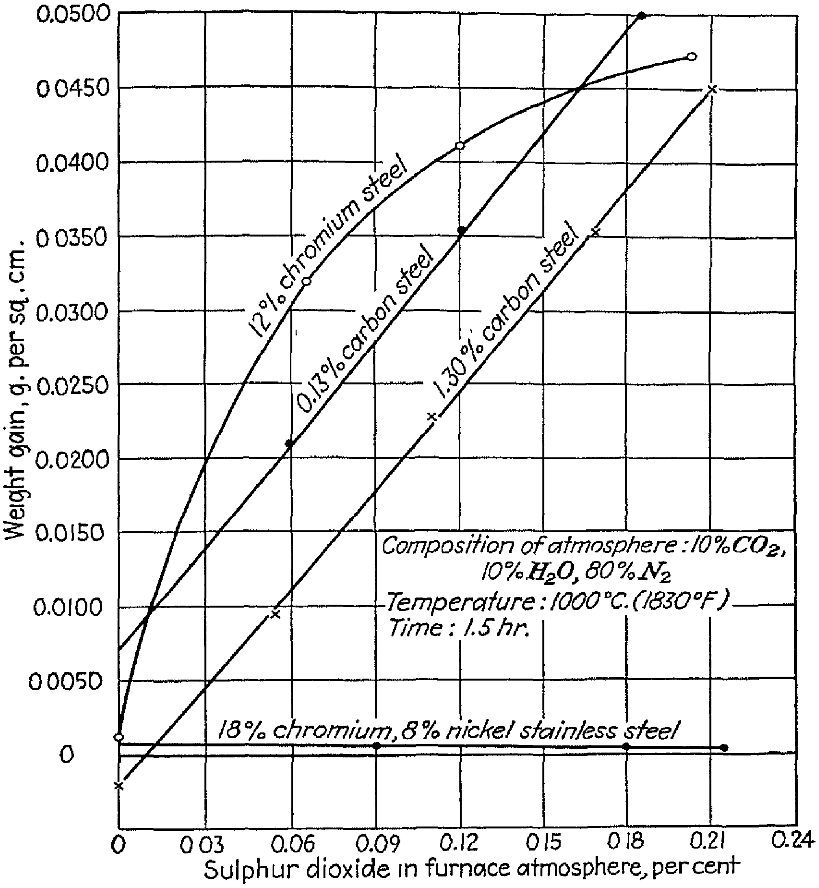

FIG. 107.—Effect of sulphur dioxide on the scaling of carbon steel, 12 per cent chromium steel, and 18-8 at 1000°C. (1830°F.). (*Preece, Richardson, Simister, and Cobb.*(526))

completely to a sulphide. Wellmann(208) reported that chromium-nickel steels are attacked by hydrogen sulphide at temperatures as low as 300°C. (570°F.).

190. Experiments of Preece and Associates on Scaling of 18-8. Owing to the care with which the work was done, the recent report by Preece and his coworkers(526) on scaling of carbon and alloy steels, including 18-8, deserves detailed attention. Specimens which were descaled electrolytically were heated at 1000°C. (1830°F.) for 1.5 hr. in an atmosphere containing 80 per cent nitrogen, 10 per cent steam, and 10 per cent carbon dioxide, to which oxygen, carbon monoxide, or sulphur dioxide was added.

The 18-8 used in the experiments contained 0.11 per cent carbon, 0.19 per cent silicon, 0.27 per cent manganese, 17.5 per cent chromium, and 8.5 per cent nickel. (The heat treatment is not given.)

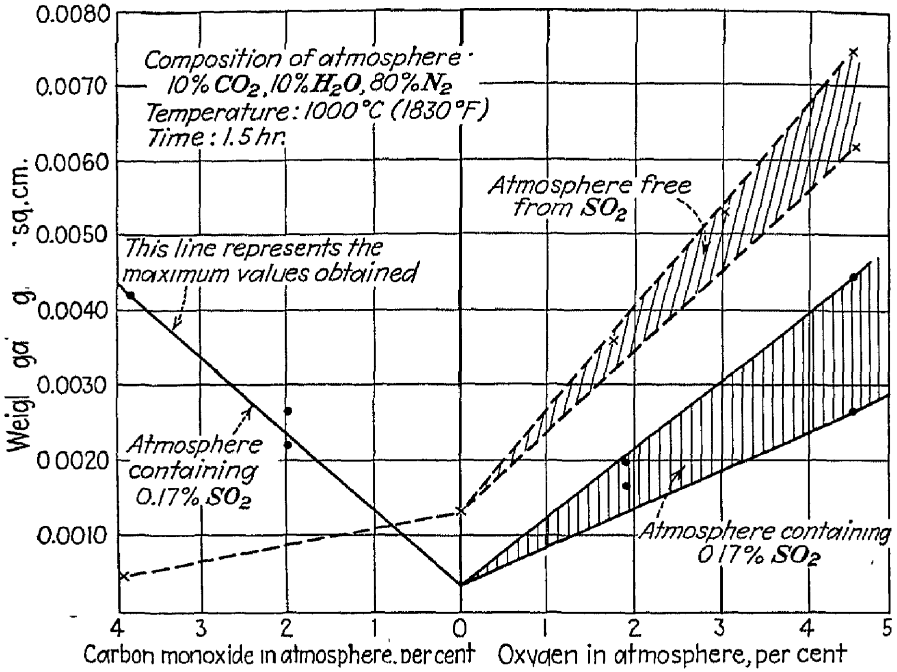

FIG. 108.—Effect of carbon monoxide, oxygen, and sulphur dioxide on the scaling of 18-8 at 1000°C. (1830°F.). (*Preece, Richardson, Simister, and Cobb* (526))

The relationship between the increase in weight and the percentage of sulphur dioxide in the furnace atmosphere for some of the steels tested, including the 18-8, is plotted in Fig. 107. The increase in the weight of 18-8 as affected by oxygen and carbon monoxide is plotted in Fig. 108. (Note that the ordinate scale for weight gain in Fig. 108 is very large.)

It is evident from Fig 107 that increase in sulphur dioxide actually decreases the already insignificant scaling rate of 18-8 slightly; this material is almost completely resistant; the other steels, on the contrary, scaled more heavily as the amount of sulphur dioxide increased.

Figure 108 indicates that carbon monoxide and oxygen added to atmospheres either containing sulphur dioxide or free from this compound have little effect on the scaling rate. In discussing the scaling of 18-8 the authors stated:

> Often the introduction of sulphur dioxide led to the formation of a stable film on the surface of the specimen, independent of the nature of the surface polish. . . . In the oxidizing atmospheres scaling occurred with the formation of ferric oxide over the dark-green film which first formed on the steel. The rate at which this film broke down was variable, and the values obtained cannot be duplicated. In Fig. [108], therefore, the results have been included in wide bands rather than by lines. The breakdown of the film and the formation of nodules of scale on the 18 per cent chromium, 8 per cent nickel steel at temperatures above 1000°C. has been observed by Wood and Rickett, and by Baeyertz who confirm at the same time the irregular mode of scaling. The specimen scaled for 8 hr. in an atmosphere containing 0.20 per cent of sulphur dioxide revealed on micro-examination no intercrystalline penetration and no modification of the alloy beneath the scale. This appeared to be due to the formation of a relatively stable film.

191. Resistance to Miscellaneous Gases and Other Reagents at Elevated Temperature.—Data obtained by Hatfield(86) on the resistance of chromium-nickel steels to two industrial gases at 900°C. (1650°F) in an open-muffle gas-fired furnace are given in Table 112. The composition of the gases was as follows:

Constituent	Percentage	
	Gas *A*	Gas *B*
Nitrogen	67.7	72.95
Oxygen	1.34	5.00
Carbon dioxide	4.75	12.00
Steam	21.10	10.00
Sulphur dioxide	0.003	0.05
Carbon monoxide	5.10	

The effect of silicon in these steels of increasing resistance to scaling is also evident.

TABLE 112.—RESISTANCE OF CHROMIUM-NICKEL STEELS TO INDUSTRIAL GASES AT 900°C. (1650°F.)*

Composition, per cent				Duration of test, hr.	Weight increase of surface, mg. per sq. cm., in	
C	Si	Cr	Ni		Gas *A*	Gas *B*
0.17	0.18	.. .	0 25	24	73.10	80 23
0.11	0.21	14.84	10.16	24	3 84	6.00
0.12	0 31	17 74	8.06	24	0.33	2.70
0.58	4.00	15.54	8 14	24	0.06	0.6

* Hatfield.(86)

Other data by Hatfield are reproduced in Table 113. These show the influence of gases such as oxygen, steam, sulphur dioxide, and carbon dioxide on unalloyed low-carbon and on chromium-nickel steels during exposure to temperatures between 700 and

TABLE 113—OXIDATION OF CARBON AND CHROMIUM-NICKEL STEELS IN VARIOUS GASES AT ELEVATED TEMPERATURES*

Steel No.	Composition, per cent					Gas	Weight increase of surface, mg. per sq. cm, at			
	C	Mn	Si	Cr	Ni		700°C (1290°F.)	800°C. (1470°F.)	900°C. (1650°F.)	1000°C (1830°F.)
1	0 17	0 67	0 18	. .	0 25	Oxygen	10 42	29.76	83.41	170.86
2	0 11	0 34	0 21	14 84	10 16	Oxygen	0 64	1 14	4 08	43 58
3	0 12	0.28	0.31	17.74	8.06	Oxygen	1.08	1.05	2 71	5 66
1	0.17	0 67	0 18	.	0.25	Steam	3 66	21 97	74.93	231 05
2	0 11	0 34	0 21	14 84	10 16	Steam	0.47	1.88	19 94	43 44
3	0 12	0 28	0 31	17 74	8.06	Steam	0 24	0.50	6.14	17 46
1	0.17	0 67	0.18	. ..	0 25	Carbon dioxide	10.03	36 74	79.92	93 46
2	0.11	0 34	0 21	14 84	10 16	Carbon dioxide	1 43	2 09	12.41	37.01
3	0 12	0 28	0 31	17.74	8 06	Carbon dioxide	0.39	1.08	3 25	5 85
1	0 17	0 67	0 18	.... .	0 25	Sulphur dioxide	9.86	41 64	177 01	†
2	0.11	0.34	0 21	14 84	10 16	Sulphur dioxide	1 06	1 16	1.72	3.75
3	0 12	0 28	0.31	17 74	8 06	Sulphur dioxide	1 43	1 65	1.83	2 63

* Hatfield.(36)

† Metal completely converted to sulphide.

1000°C. (1290 and 1830°F.). In each instance the higher chromium steel had the greater resistance to oxidation.

Musatti and Reggiori(329) investigated the effect of sulphur dioxide and of air at 500 to 800°C. (1930 to 1470°F.) on the mechanical properties of 18-8 steels. They found that at these temperatures intergranular penetration occurred with a resultant loss in strength. Sergeson(126) reported Charpy impact values for 18-8 steels of more than 50 ft-lb. at 815°C. (1500°F.) but stated that in service these values may be lower if corrosion is involved. Work by Gruber(141) on a 25 per cent chromium, 25 per cent nickel steel, at temperatures between 700 and 1000°C. (1290 and 1830°F.), showed that at the higher temperatures of this range attack by sulphur-bearing gases increased materially. Pilling and Worthington(196) discussed at length the published data on the effect of temperature on iron-chromium-nickel alloys. They indicated that, if enough chromium is present, chromium-nickel steels are satisfactorily resistant to gases containing sulphur dioxide at relatively high temperatures.

Cox(262) observed that hydrogen at 500°C. (930°F.) and up to 3000 lb. per sq. in. pressure did not attack 18-8 or 25-20 steels; but he emphasized that the carbon should be low. Inglis and Andrews,(278) however, showed that, although the low-carbon 18-8 material is not disintegrated by hydrogen at 450°C. (840°F.) and 3750 lb. per sq. in. pressure, it "absorbs large quantities of hydrogen and consequently suffers severe embrittlement. The ductility can be restored by heating to expel the absorbed hydrogen."

According to Imhoff,(145) austenitic chromium-nickel steels are attacked by molten zinc. Experiments have shown also that such steels are attacked by molten copper, molten brass, and mercury vapors. The attack consists of penetration of the grain boundaries by the molten metals. Other molten non-ferrous metals, having appreciably lower melting points, do not function in the same manner. For instance, molten tin and solder do not penetrate the grain boundaries when they are not superheated too far above their melting point. Tour,* however, reported that molten aluminum and aluminum alloys attack these steels, dissolving the surface without marked preferential solution of the grain boundaries.

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* S. Tour, private communication.

B. CORROSION OF CHROMIUM-NICKEL STEELS IN VARIOUS MEDIA

The effect of chromium on the corrosion resistance of iron is well known. Quoting from the first volume of this monograph:

> When chromium is present in the matrix proper and as carbides, the corrosion resistance of alloys is a function of the chromium content of the matrix. This function is not a direct one, because the resistance to attack increases very slowly with small percentages of chromium but becomes marked when the chromium content reaches approximately 4 per cent and increases very rapidly as the chromium content passes 10 per cent.

This statement is as true for alloys of iron, chromium, and nickel as it is for alloys of iron and chromium with no nickel.

192. Atmospheric Corrosion of Chromium-nickel Steels.—Strauss(64) studied the electrochemical behavior of chromium-nickel steels to determine whether their passivity was due to the combination of oxygen atoms with the surface atoms of iron, chromium, and nickel but arrived at no definite conclusions. Later, Forrest, Roetheli, and Brown(136) found that initially the corrosion rates of ordinary carbon steel and of 18-8 were of the same magnitude, but after a few minutes the corrosion rate for the 18-8 steel became zero. Evans and Stockdale(112) isolated the passive film and Hoar and Evans(229) subsequently discussed the entire phenomenon at length. It was shown that, if the corroding media were strong enough to break down this film continually, the 18-8 steel would corrode as rapidly as ordinary steel. Cournot(176,177) determined the effect of surface condition on corrosion resistance and also different methods for testing steels in this respect. He concluded that the smoother the surface the greater is the resistance to corrosive attack, and that the most consistent results are secured in immersion and emersion tests. Smith(510) gave potential-time curves for three common types of chromium-nickel steels as measured against potassium chloride, and Uhlig and Wulff(528) reviewed the subject at length and presented evidence against a film consisting of strictly chemical compounds of oxygen.

The whole theory of passivation by an oxide film has been questioned seriously by Uhlig and Wulff,(528) who postulated electron sharing of elements in the transition groups, with hydrogen acting to displace electrons and oxygen tending to prevent such hydrogen action. They further suggested the possibility of an oxygen film similar in effect to the usual passive film. The mechanism, however, is not that of the protective film of the paint or varnish type, but rather of a film which reacts with hydrogen and prevents hydrogen from destroying the shared electron balance in the alloy. In this connection Uhlig and Wulff measured potentials on various types of chromium-nickel steels with and without molybdenum and showed critical breakdown voltages which correspond to attack. They considered it significant that where attack was marked the corrosion product contained bivalent rather than trivalent iron. Discussers of Uhlig and Wulff's paper, however, felt that the experimental evidence was not conclusive. Further work is clearly needed.

Exposure to the atmosphere presents a good opportunity for the formation of a protective film. Under this condition, the 18-8 steel and steels of higher chromium and nickel contents remain bright indefinitely if the metal is kept reasonably clean. This has been established by the long exposure in service of polished sheets, strips, and bars in ornamental and structural applications, although in this connection the danger of rust spots owing to iron contamination of the surface by mechanics' tools and iron dust should be mentioned.

TABLE 114.—CORROSION IN NITRIC ACID OF A STEEL CONTAINING 0.09 PER CENT CARBON, 0.47 PER CENT MANGANESE, 0.33 PER CENT SILICON, 18.45 PER CENT CHROMIUM, AND 8.76 PER CENT NICKEL, AIR COOLED FROM 1050°C. (1920°F.)

Acid concentration, per cent	Temperature	Duration of test, hr.	Weight loss, mg. per sq. dm. per day
1	Boiling	18	Nil
3	Boiling	18	Nil
20	Boiling	18	Nil
20	Room temperature	18	Nil
65	Room temperature	41	Nil
65	Boiling	144	123 5

193. Acid Corrosion of Chromium-nickel Steels.—Nitric acid is a strong oxidizing agent; as shown in Table 114, an 18-8 steel containing 0.09 per cent carbon is not appreciably attacked by